The First Stars and Galaxies, Chemical Evolution, and the Milky Way

Jason Tumlinson

SPACE TELESCOPE SCIENCE INSTITUTE

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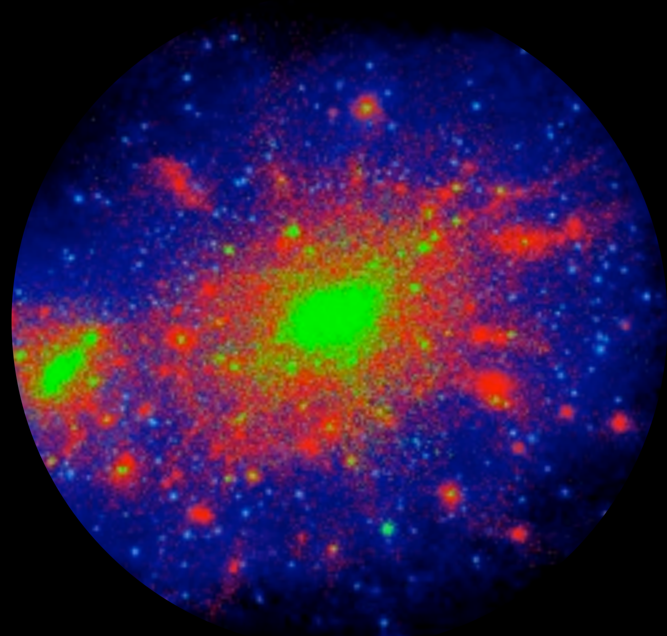
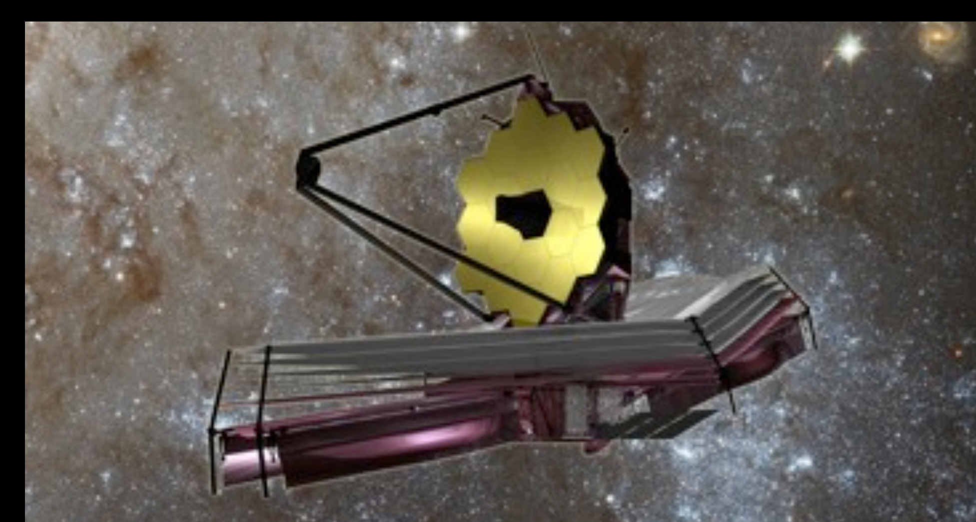
Theme: What does the Milky Way teach us about Cosmic Chemical Evolution?





CCE and the MW in Four Easy Lessons

Lesson 1

The “Fossil Record” can fill a gap in our high-z knowledge.

Lesson 2

Early Chemical Evolution is Hierarchical and Stochastic.

Lesson 3

Early Star Formation and Nucleosynthesis Was “Weird”

Lesson 4

Pursuing High-z / Low-z links is essential.

Hot Topics in the Study of the "First Stars"

1. What was the IMF of primordial stars?

- Simulations (Abel et al. 2002, Bromm et al. 2002; Yoshida et al. 2006, O'Shea et al. 2007) indicate mass scales of 10s to 100s $M_\odot$ owing to inefficient cooling in primordial gas. Feedback limits final mass to <~ 200 $M_\odot$ (Tan & McKee '07). *This is a very strong prediction of theory.*

- These simulations cannot yet predict the final masses, and even if they could observational tests of the IMF are needed.

2. When did the first low-mass stars form? Under what conditions?

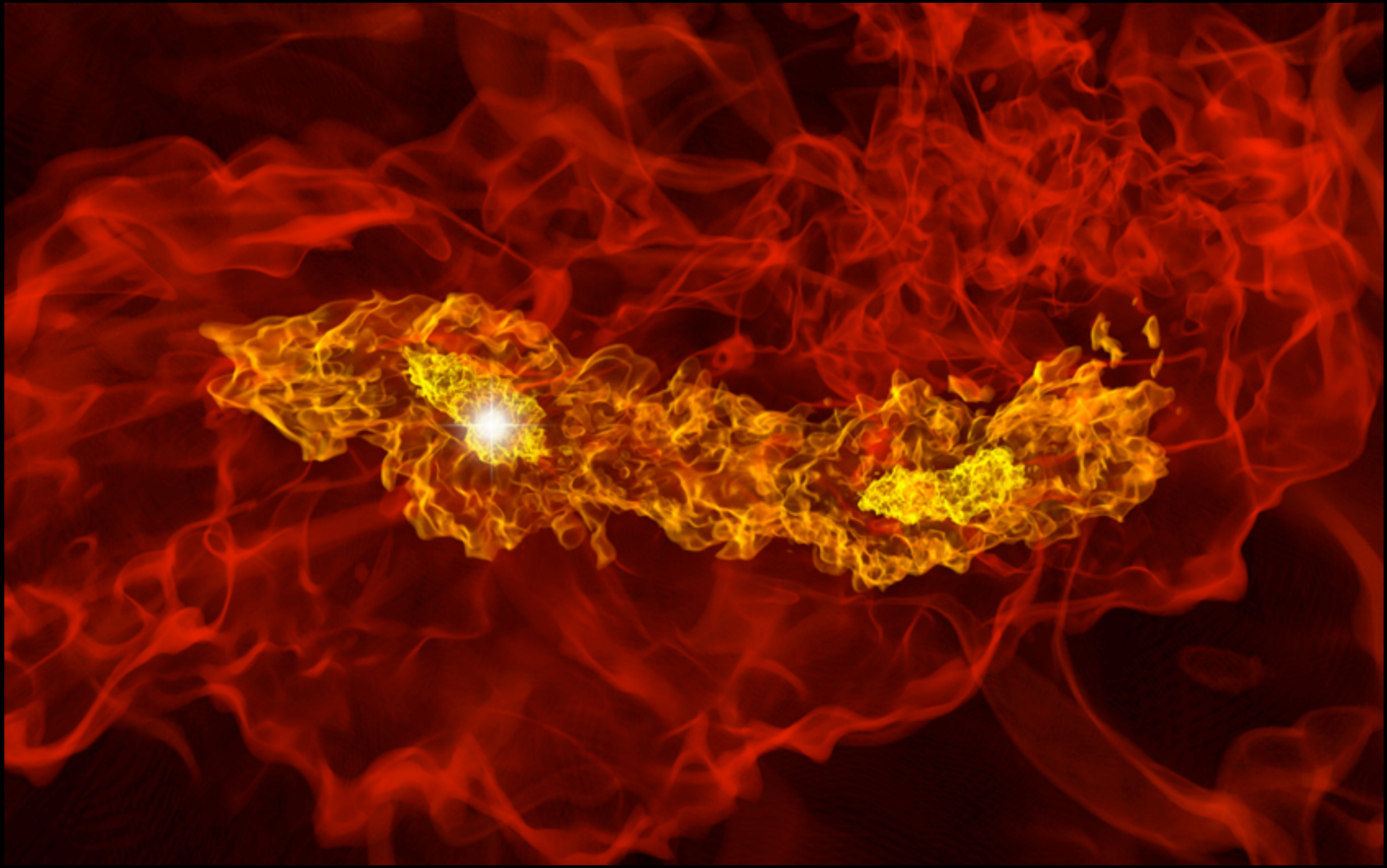
- Theoretically defined "critical metallicity", Z_{crit}, ~ 10^{-4} $Z_\odot$, required for efficient fragmentation to low-mass stars, but this boundary is blurred by local conditions.

- The IMF may not become "normal" until much higher metallicity, depending on local conditions, the global radiation background, and the CMB.

3. Did the first stellar generations yield novel types of SNe, or unusual yields?

- Extremely energetic "Pair Instability Supernovae" or "hypernovae"?

- We would also like to isolate the first sources of rare heavy elements.



Turk et al. 2009, Science, 325, 601

Simulations tell us that the first stars formed in isolation, or perhaps in binaries or small clusters, in the first virialized halos of $T \sim 10^{3-4}$ K at $z = 35 - 15$.

Why Pursue the Fossil Record?

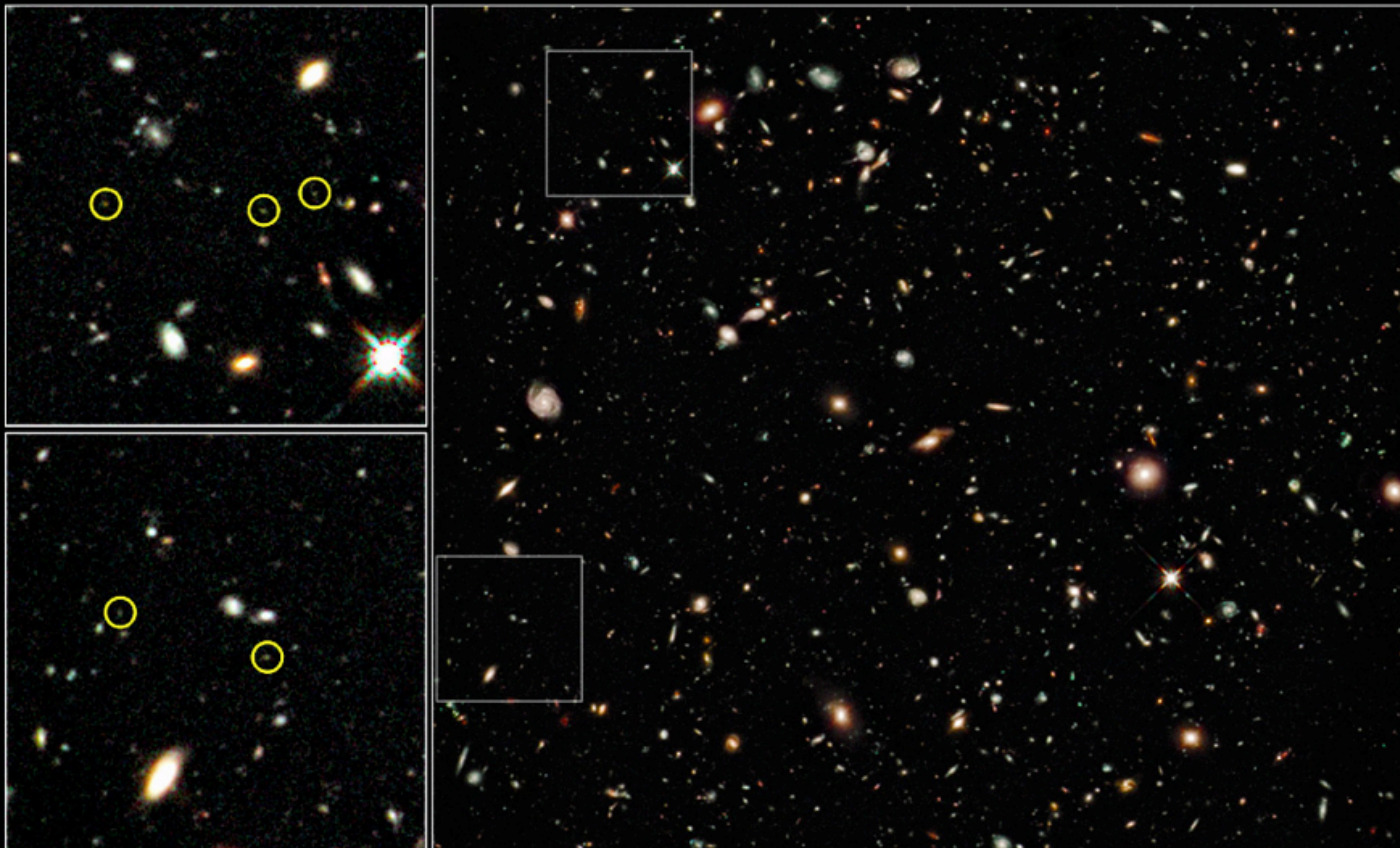
We want “to understand how the first stars and galaxies formed, and how they change over time into the objects recognized in the present Universe.” (NASA Strategic Research Objective 3D.2)

For many astronomers, this means “deep fields” to study galaxy light at high redshift, and to examine their luminosity, mass, star formation history, and other properties of the population.

This frontier was recently advanced to $z \sim 8$ by Hubble’s new Wide Field Camera 3, giving a small taste of what JWST offers.

Why Pursue the Fossil Record?

Hubble Ultra Deep Field • Infrared *Hubble Space Telescope* • WFC3/IR



NASA, ESA, G. Illingworth (UCO/Lick Observatory and University of California, Santa Cruz), and the HUDF09 Team STScI-PRC10-02

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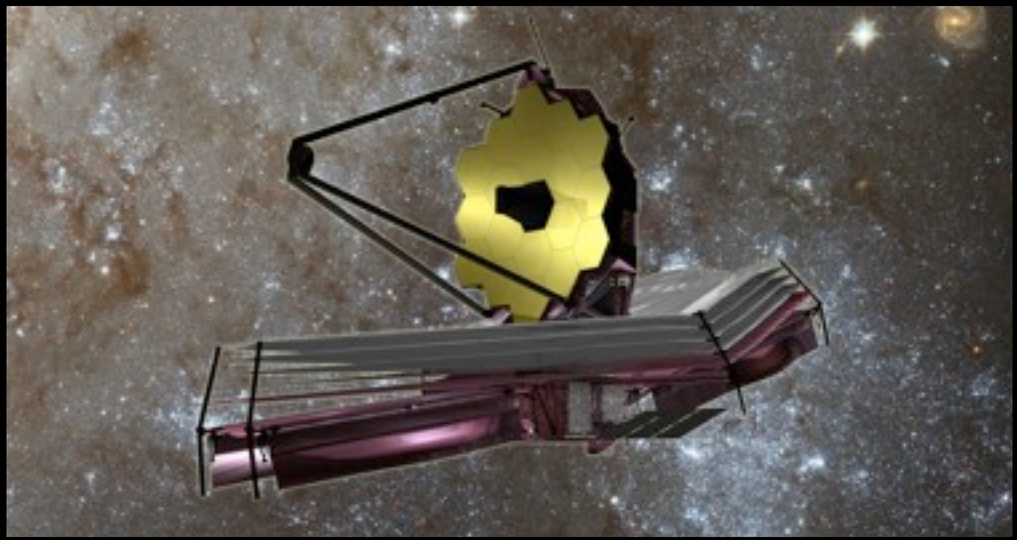

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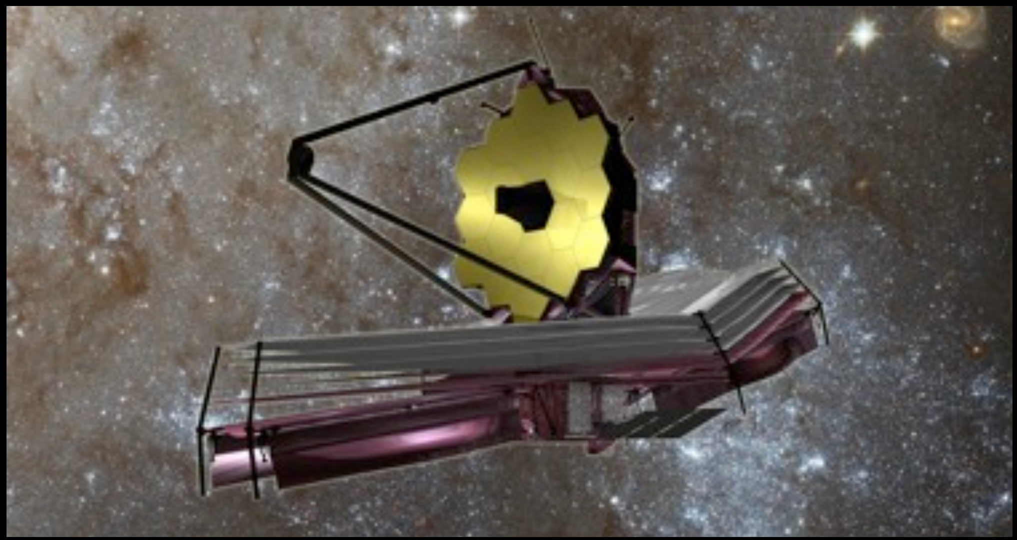

But . . .

Won’t JWST See the First Stars?

First Light and Reionization :
open questions in the post-JWST era

Massimo Stiavelli
STScI

and

John Mather (NASA/GSFC, chair)
Mark Clampin (NASA/GSFC)
Rene Doyon (U. of Montreal)
Kathy Flanagan (STScI)
Marijn Franx (Leiden U.)
Jonathan Gardner (NASA/GSFC)
Matthew Greenhouse (NASA/GSFC)
Heidi Hammel (SSI)
John Hutchings (Herberg I. of A.)
Peter Jakobsen (ESA)
Simon Lilly (ETH-Zurich)
Jonathan Lunine (U. of Arizona)
Mark McCaughrean (U. of Exeter)
Matt Mountain (STScI)
George Rieke (U. of Arizona)
Marcia Rieke (U. of Arizona)
George Sonneborn (NASA/GSFC)
Rogier Windhorst (Arizona State U.)
Gillian Wright (UK ATC)

(the JWST Science Working Group)

Won't JWST See the First Stars?

Isolated Population III stars will also be relatively faint in the non-ionizing continuum (AB~38.5-40 at z=10-25, compared to AB~31 achievable in 10^5 s exposures by JWST), because most of their energy output is in the ionizing continuum (Bromm et al. 2001b, Tumlinson et al. 2003) which is efficiently absorbed by the IGM. Thus, they will be impossible to detect directly with JWST.

7. Summary

The above discussion suggests that two very difficult and important questions pertaining to the First light and reionization epoch will still need to be answered in the post-JWST era: i) When and how did the first stars form? And ii) When and how did the active galactic nuclei form? This should be this field active and exciting even in the next decade. Conversely we expect that progress in our understanding of the first galaxies and reionization will be major and such that at this stage it would be hard to predict what further studies, if any, might be required.

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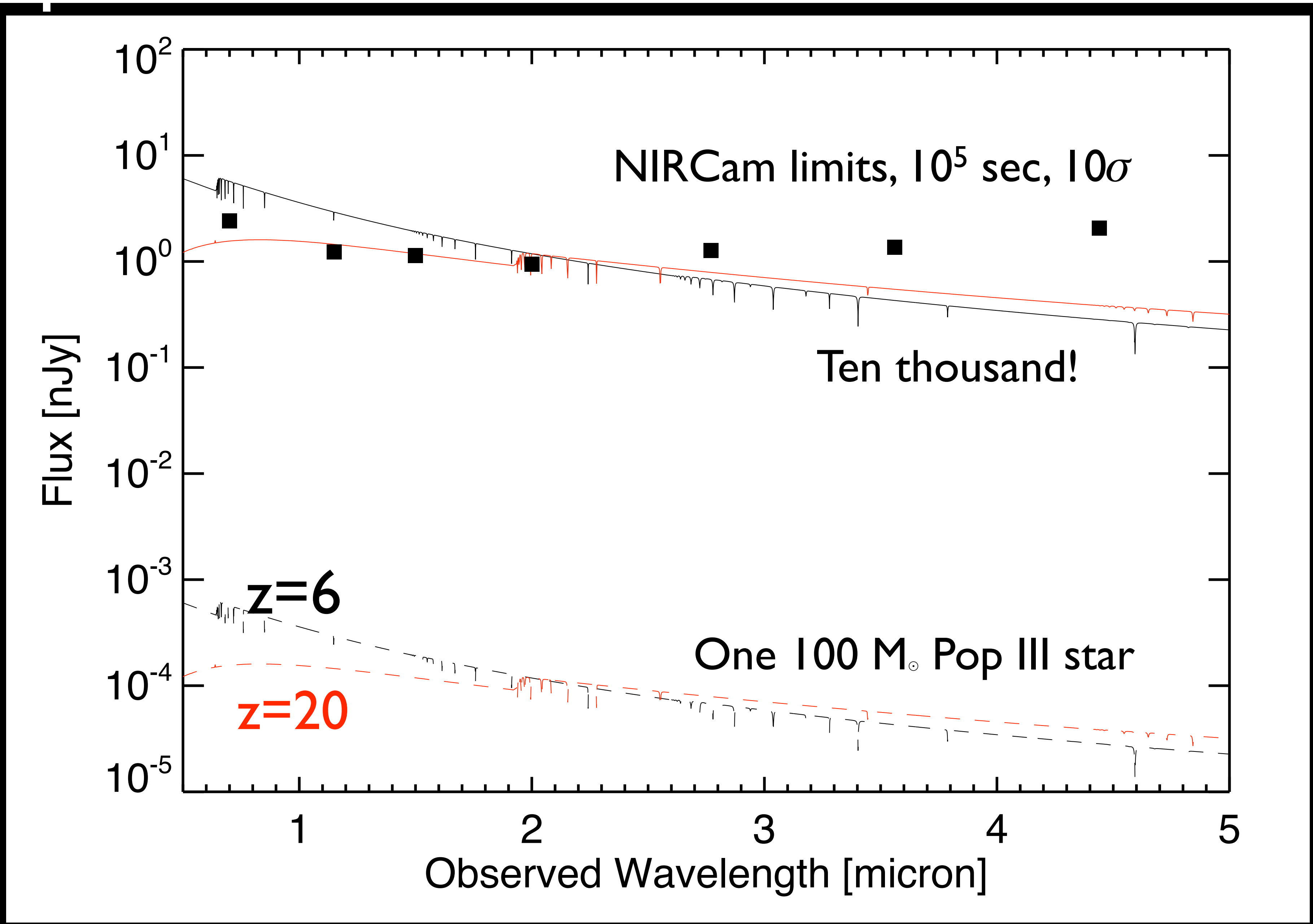
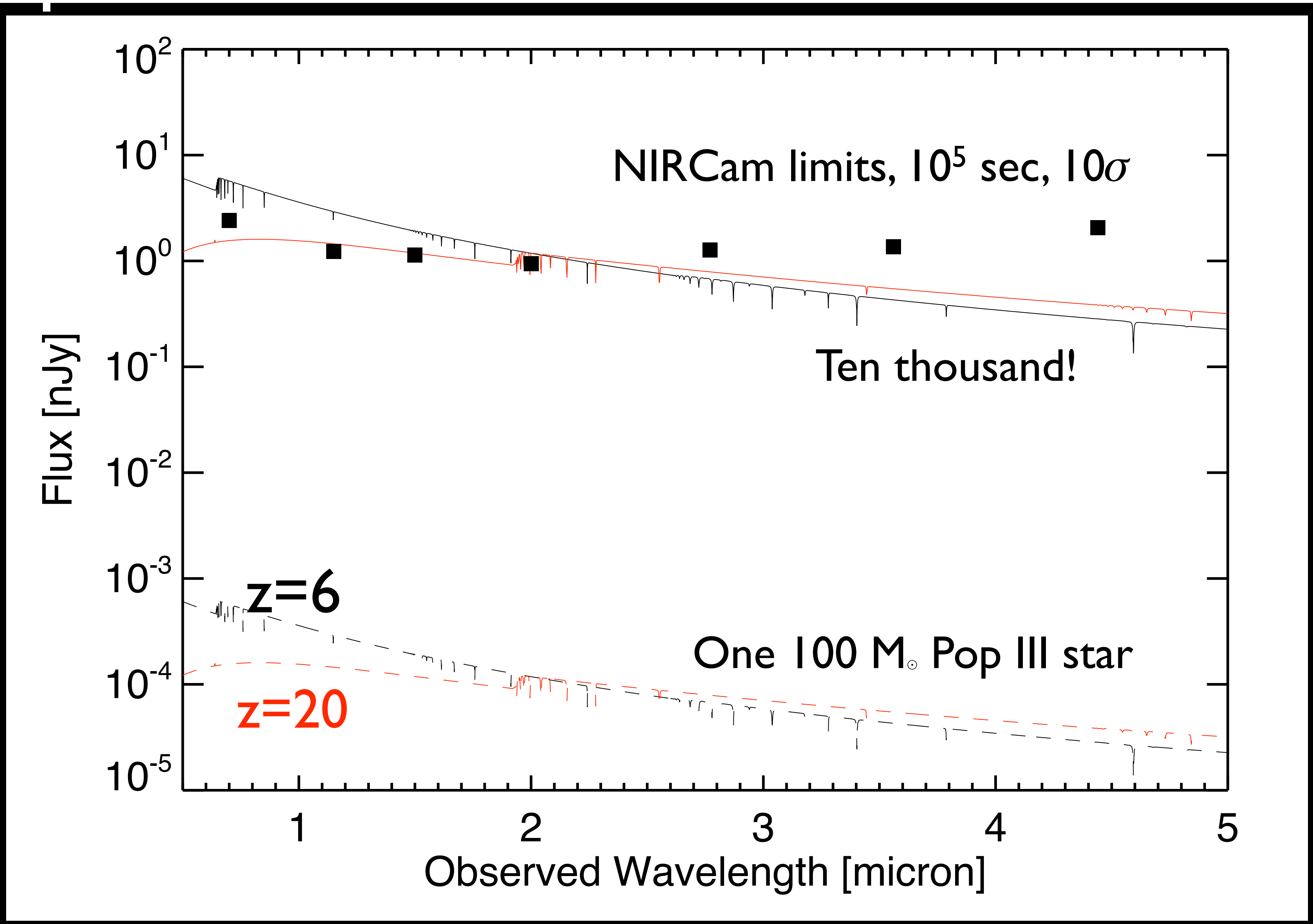
It turns out that if our theory of the first stars is correct, it will be nearly impossible to detect them directly in the high-redshift Universe!

Is the Pop III to II transition visible where it occurred?



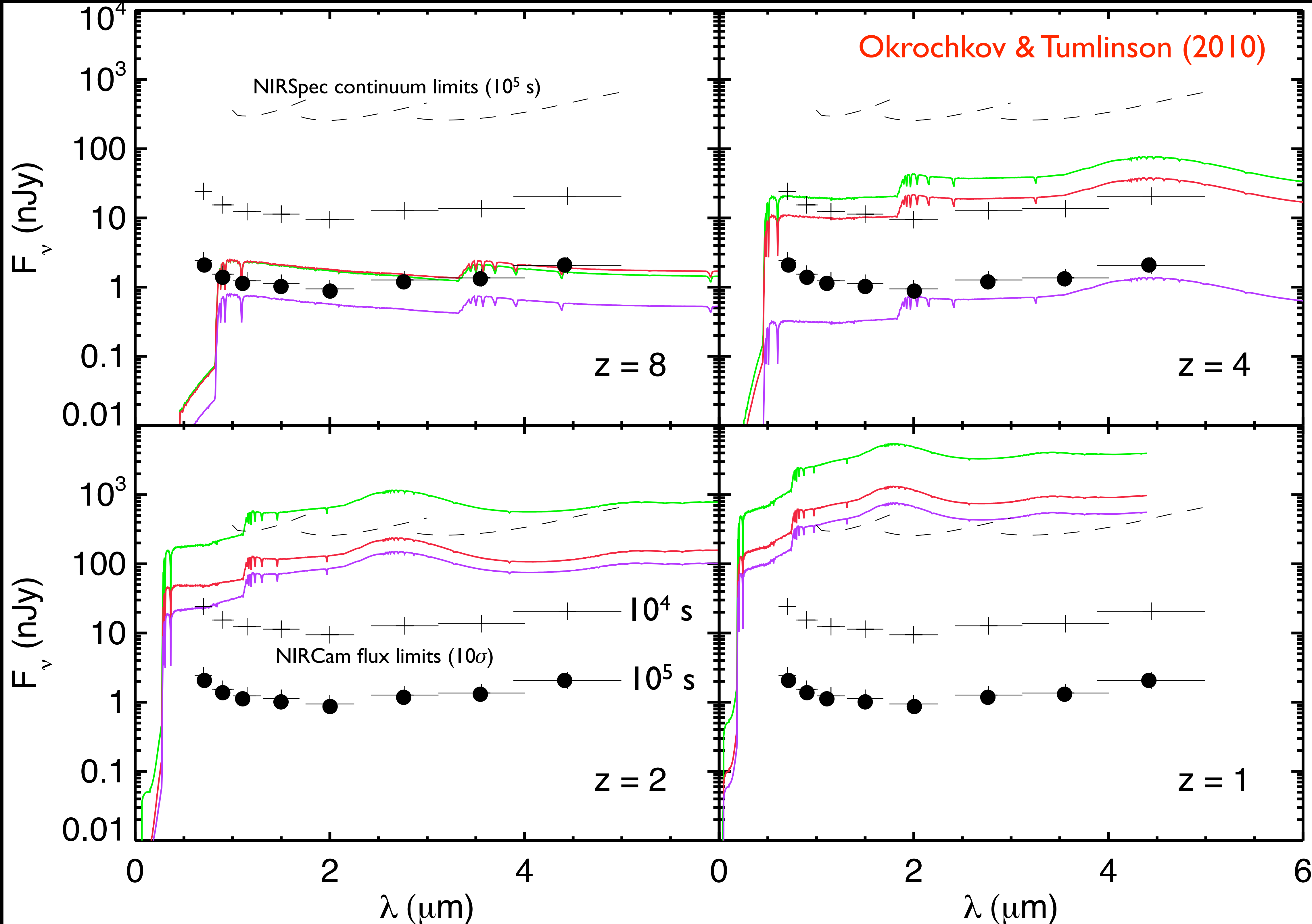
Is the Pop II to II transition visible where it occurred?



If our theory of the first stars is correct - one massive star per minihalo or small clusters in 10^4 K halos - it will be nearly impossible to detect them directly in the high-z Universe!

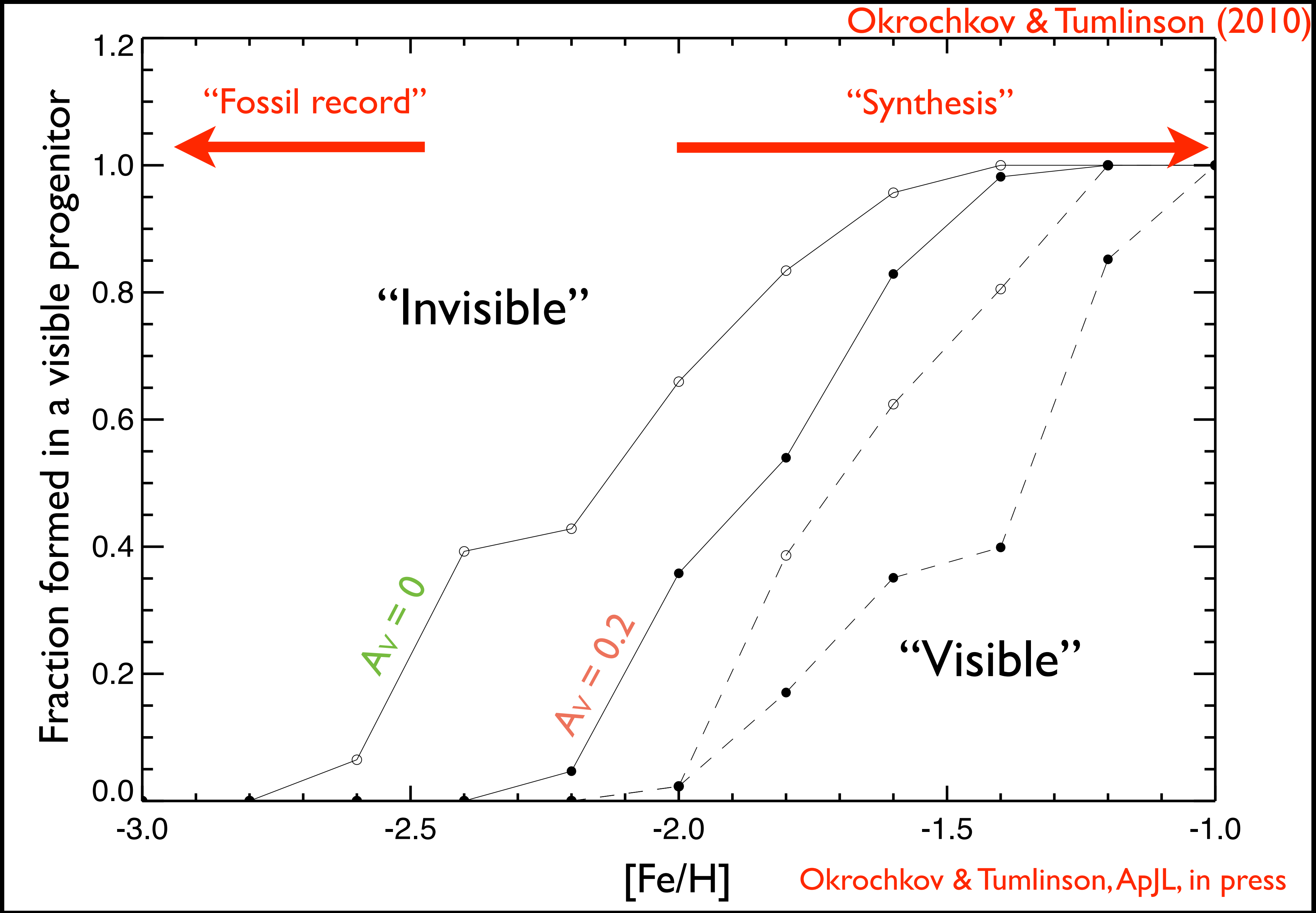
Now what?

High Redshift Visibility of Milky Way Progenitors



MW progenitors visible to z ~ 6 - 8 in JWST deep fields (~dust). Each one deposits some stars into the MW halo - how do the low-z stars and the high-z visibility relate?

The High-Redshift Visibility vs. Metallicity

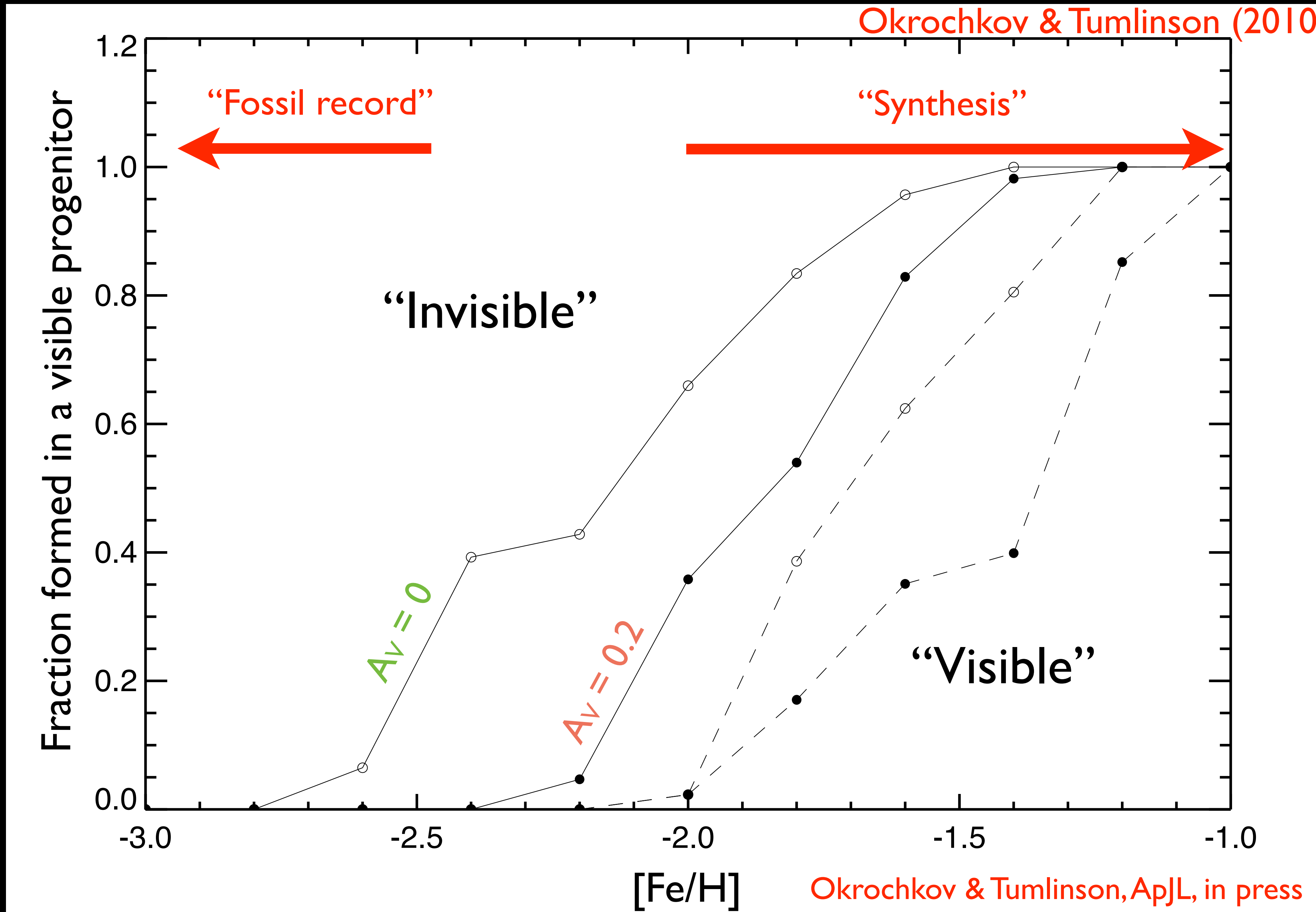


Now: there are two kinds of stars that survive in the MW halo.

1) Those that formed in progenitors NIRCam can see: [Fe/H] ⪆ -2

2) Those that formed in progenitors NIRCam cannot see: [Fe/H] ⪅ -2

The High-Redshift Visibility vs. Metallicity



Now: there are two kinds of stars that survive in the MW halo.

1) Those that formed in progenitors NIRCam can see: [Fe/H] $\gtrsim$ -2

2) Those that formed in progenitors NIRCam cannot see: [Fe/H] $\lesssim$ -2

So, the "Fossil Record" can fill a gap in our high-z knowledge.

CCE and the MW in Four Easy Lessons

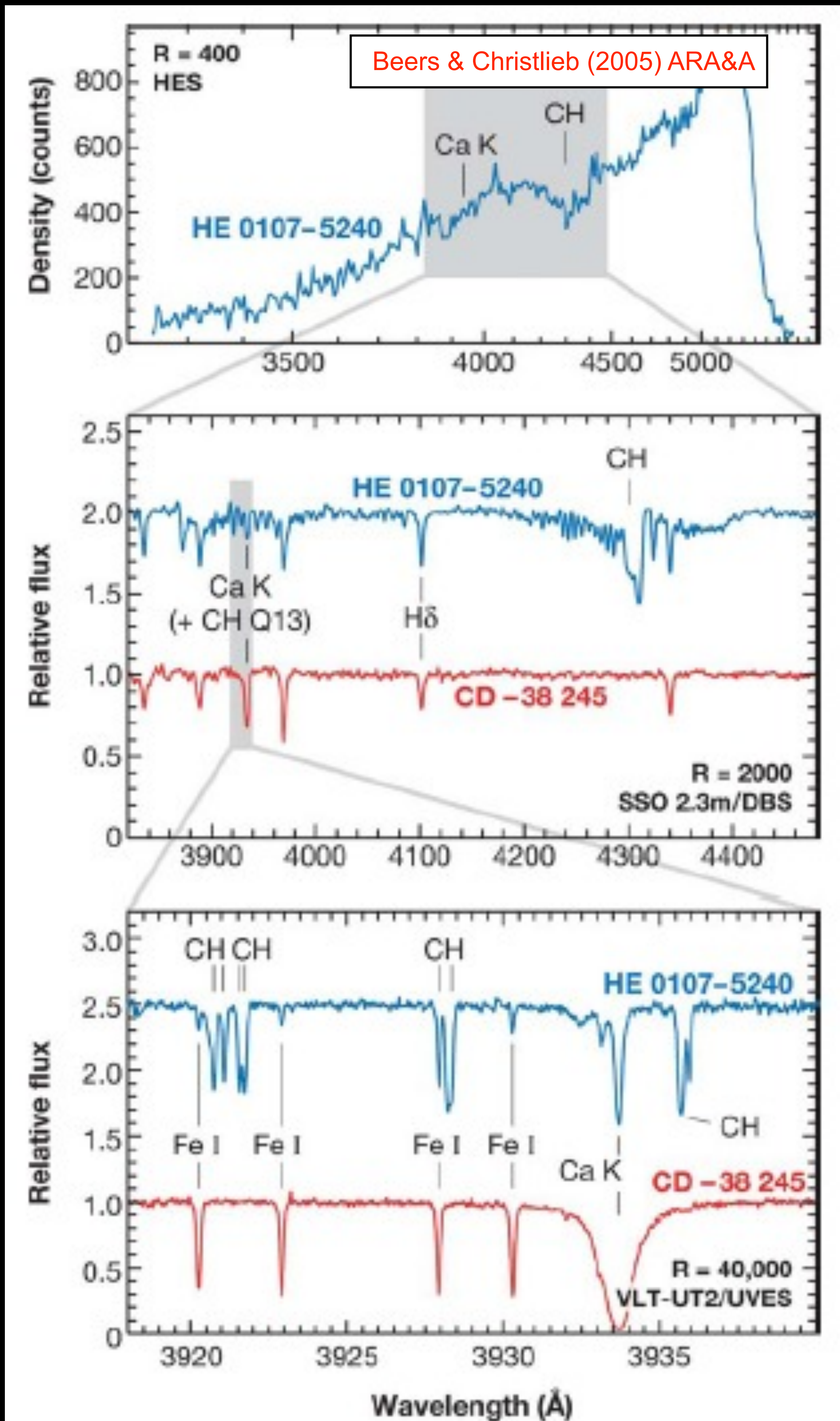
Lesson 1

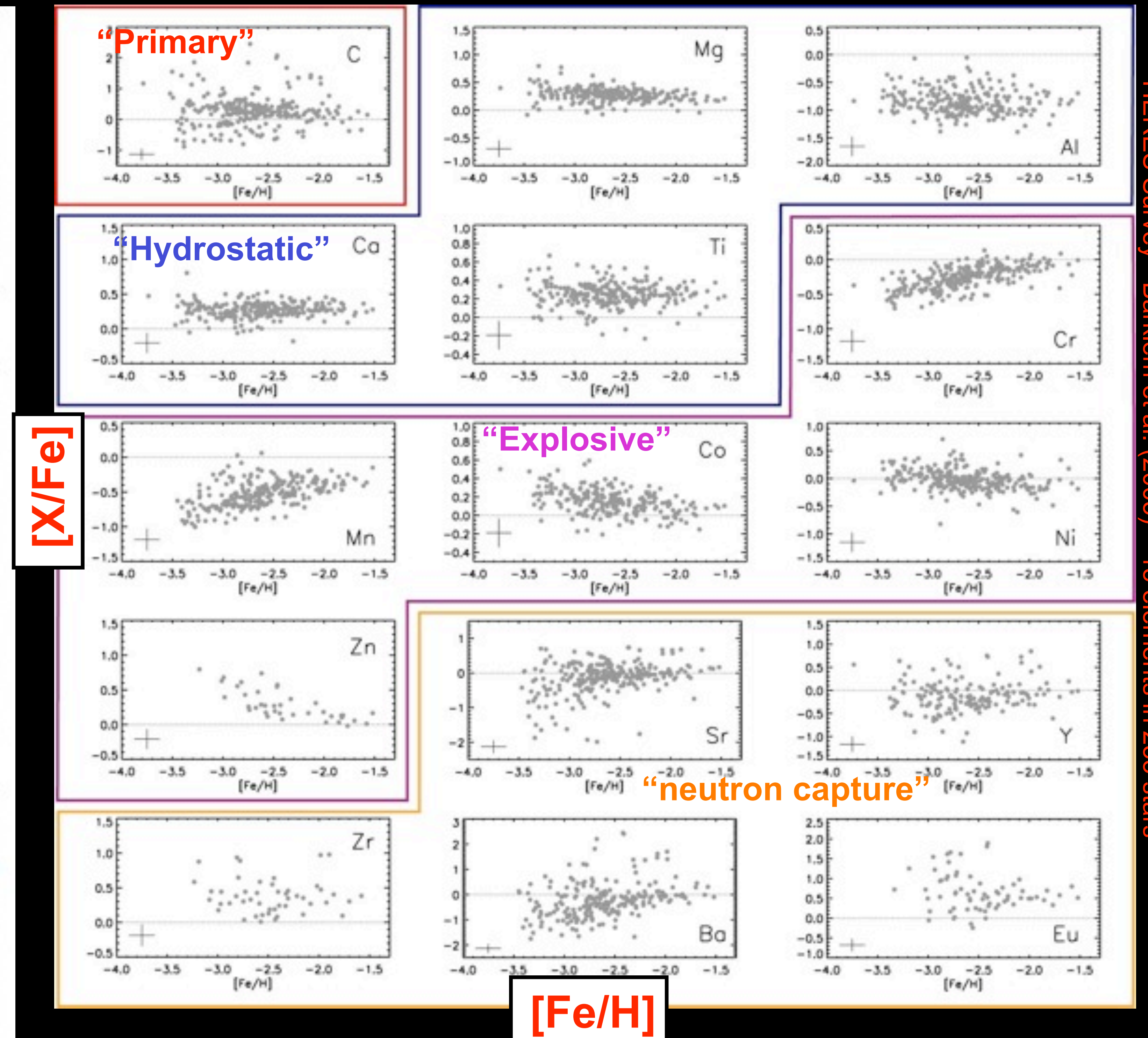
The "Fossil Record" can fill a gap in our high-z knowlege.

Lesson 2

Early Chemical Evolution is Hierarchical and Stochastic.

The "Fossil Record"



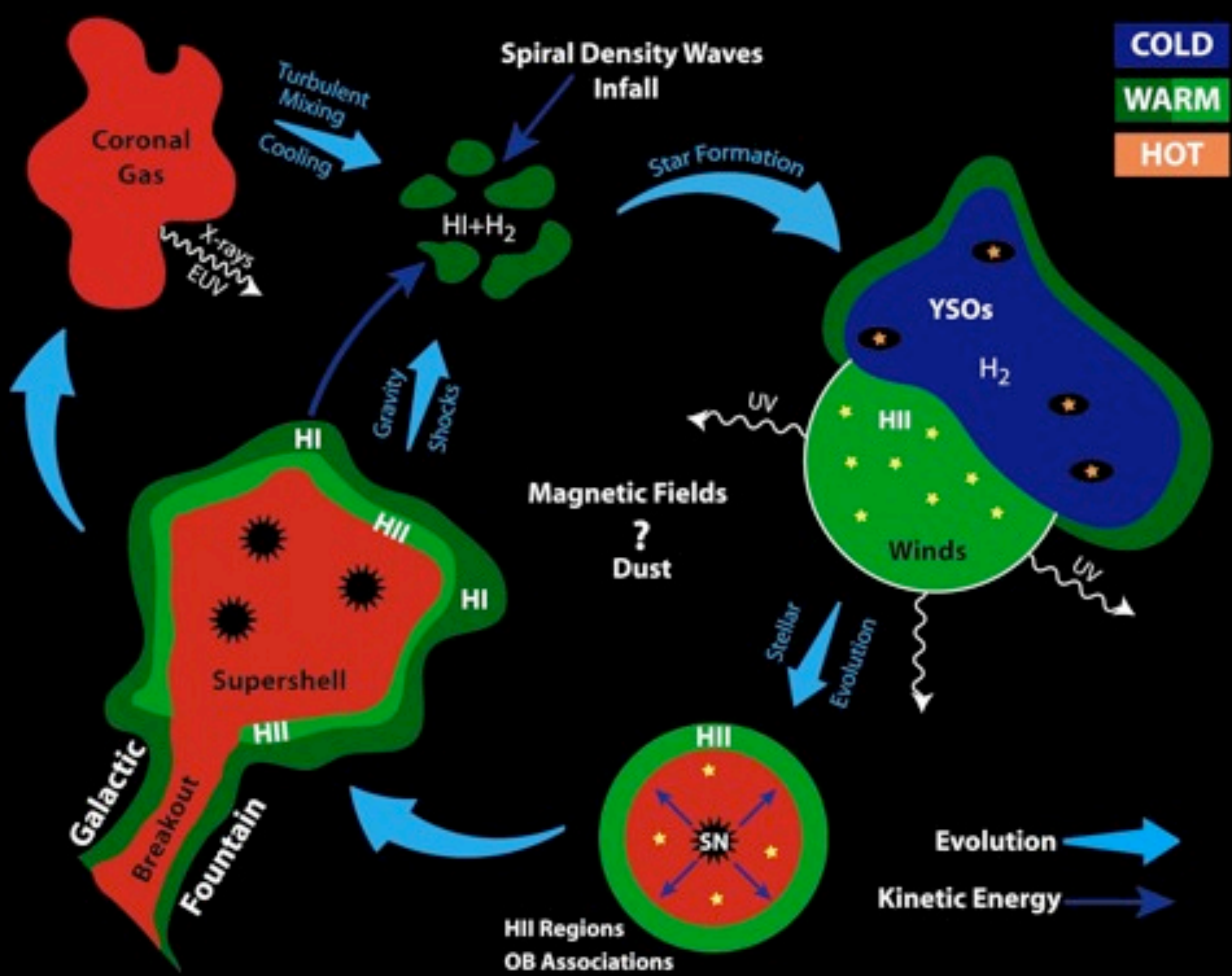


Measured <u>proper motion</u>, <u>radial velocity</u>, and <u>position</u> trace galactic components – disk, bulge, or halo.

<u>Color</u>, <u>luminosity</u>, <u>T_{eff}</u>, and <u>metallicity</u> select old, low-mass stars with [Fe/H] < -2 that most likely trace the first generations.

The Problem

Observable quantities (stellar parameters, [X/Fe], orbit) are complex, emergent, stochastic functions of many coupled physical processes.



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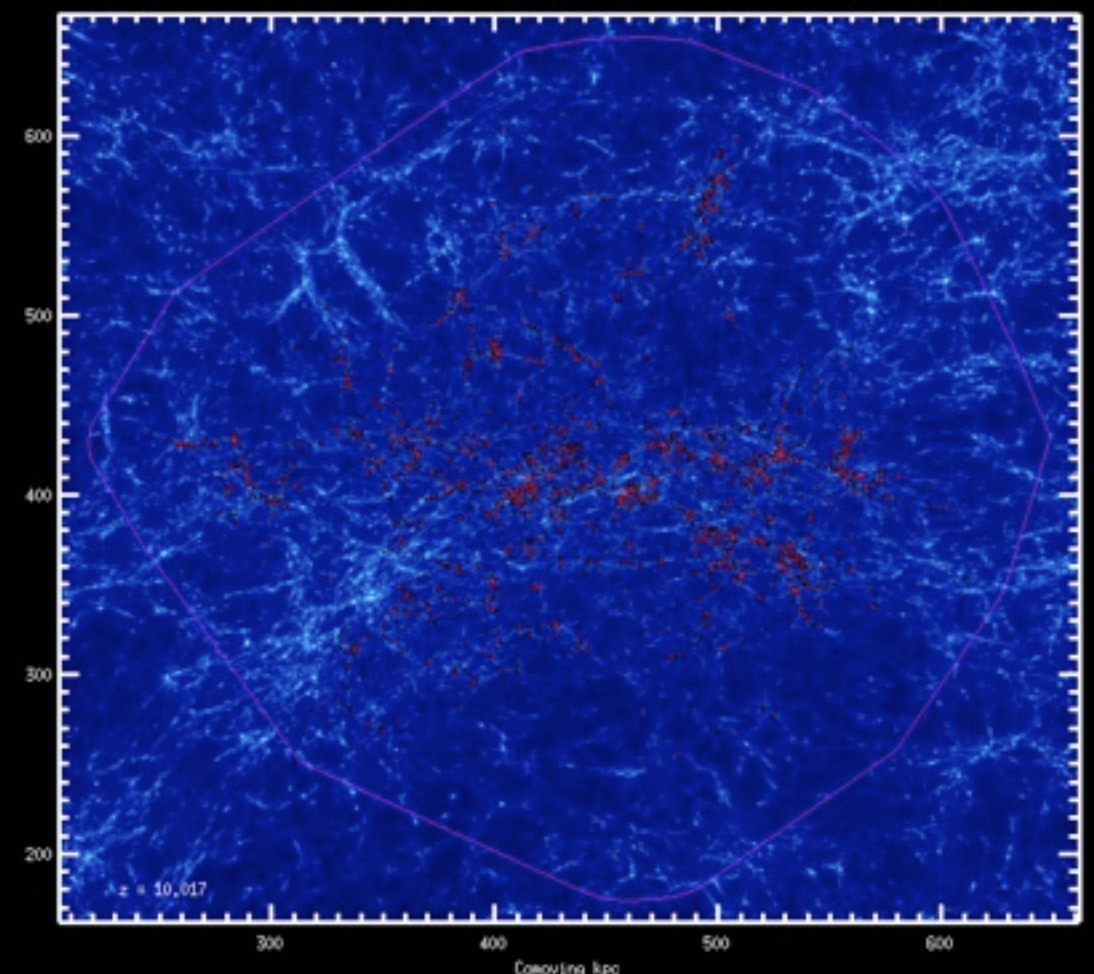
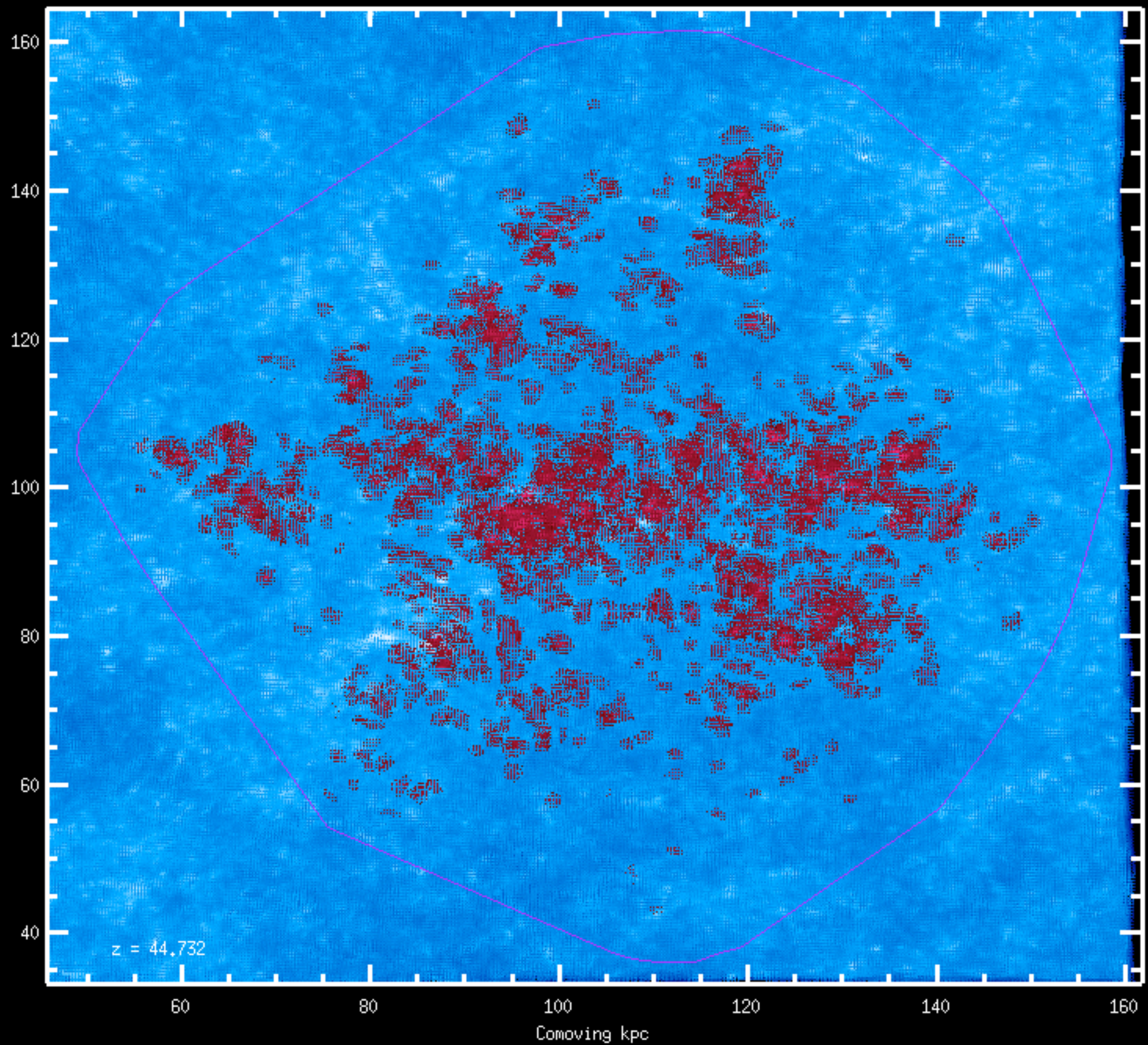
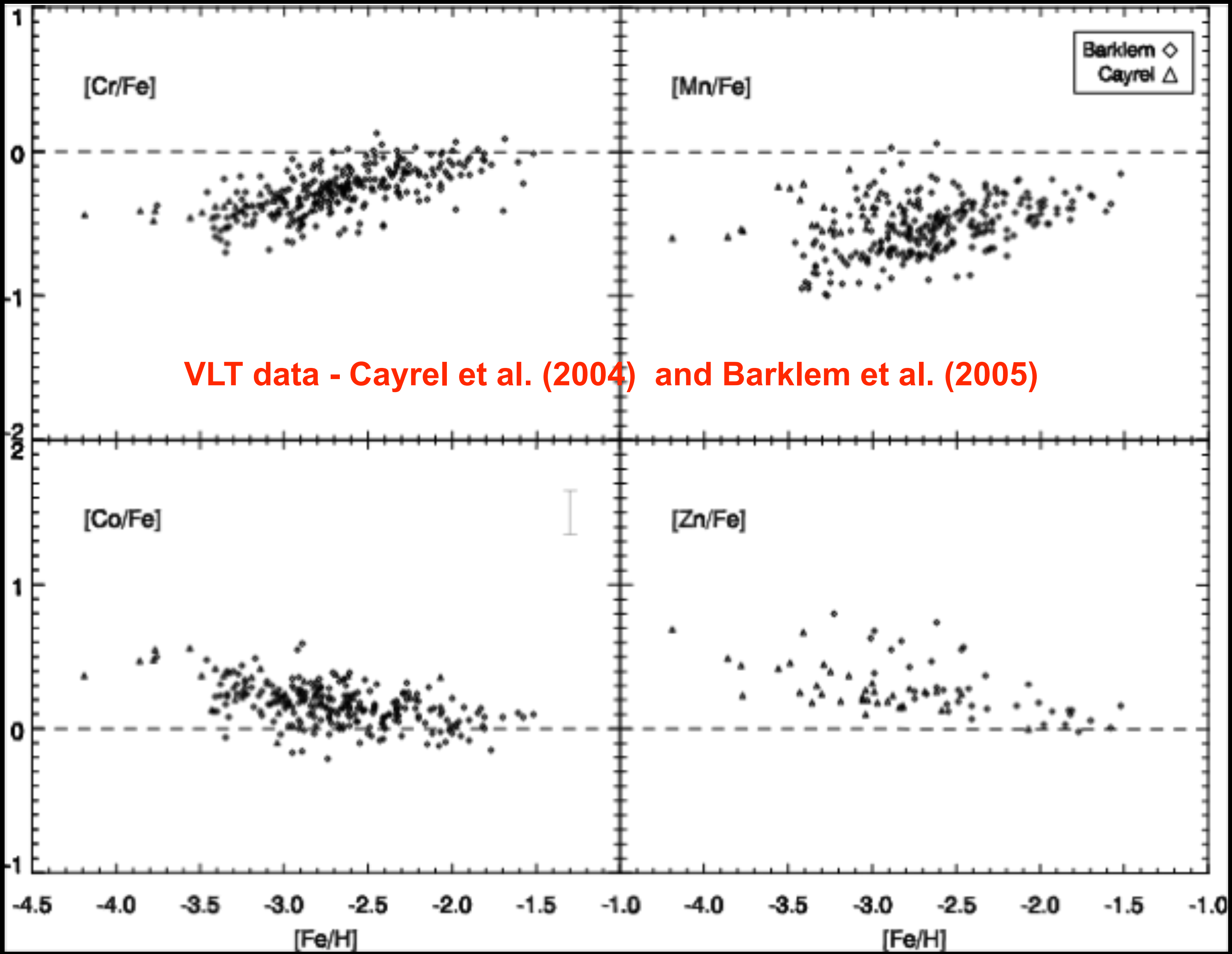


Chemical Evolution Is Hierarchical



Chemical Evolution is Stochastic - Need SAMPLES



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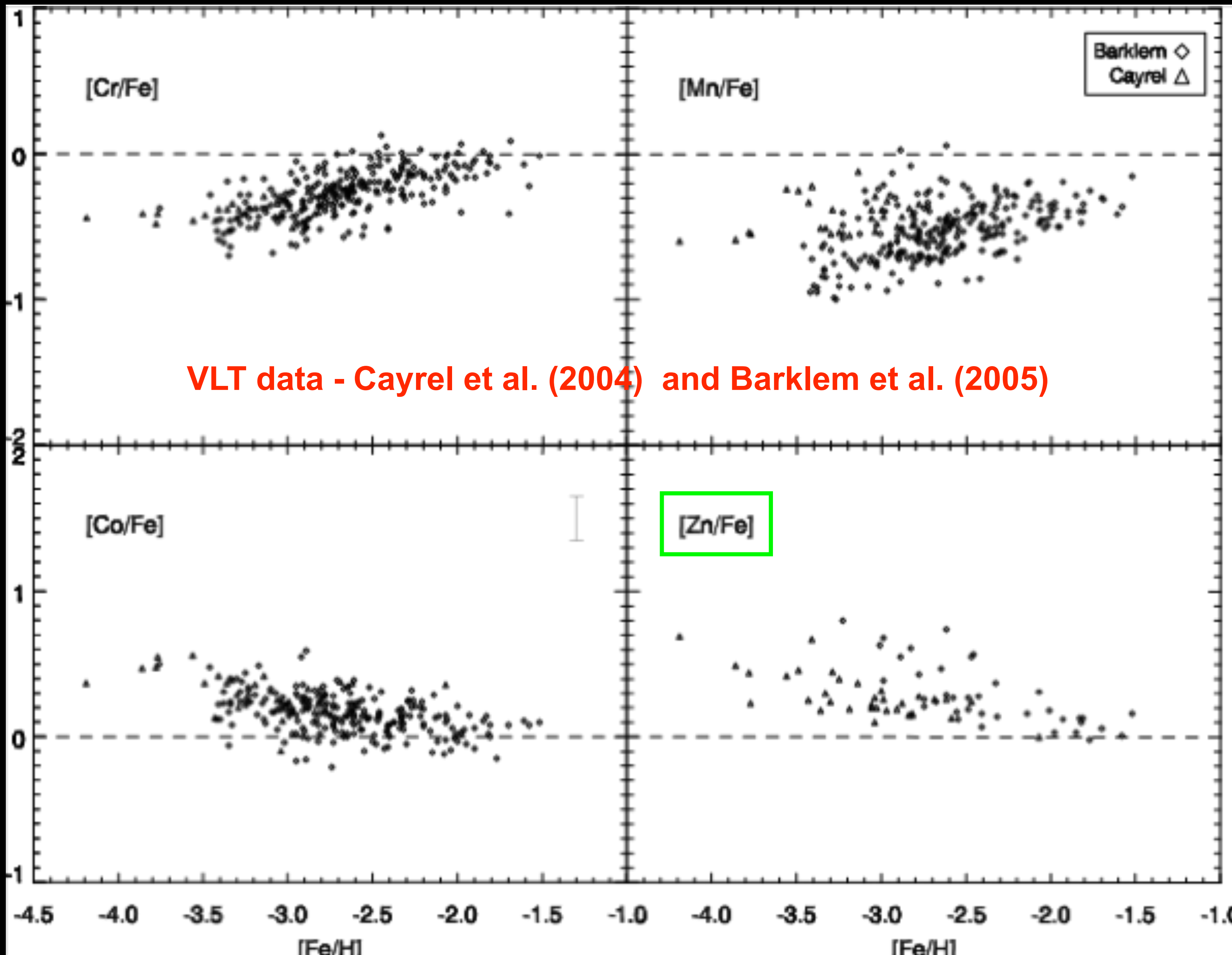

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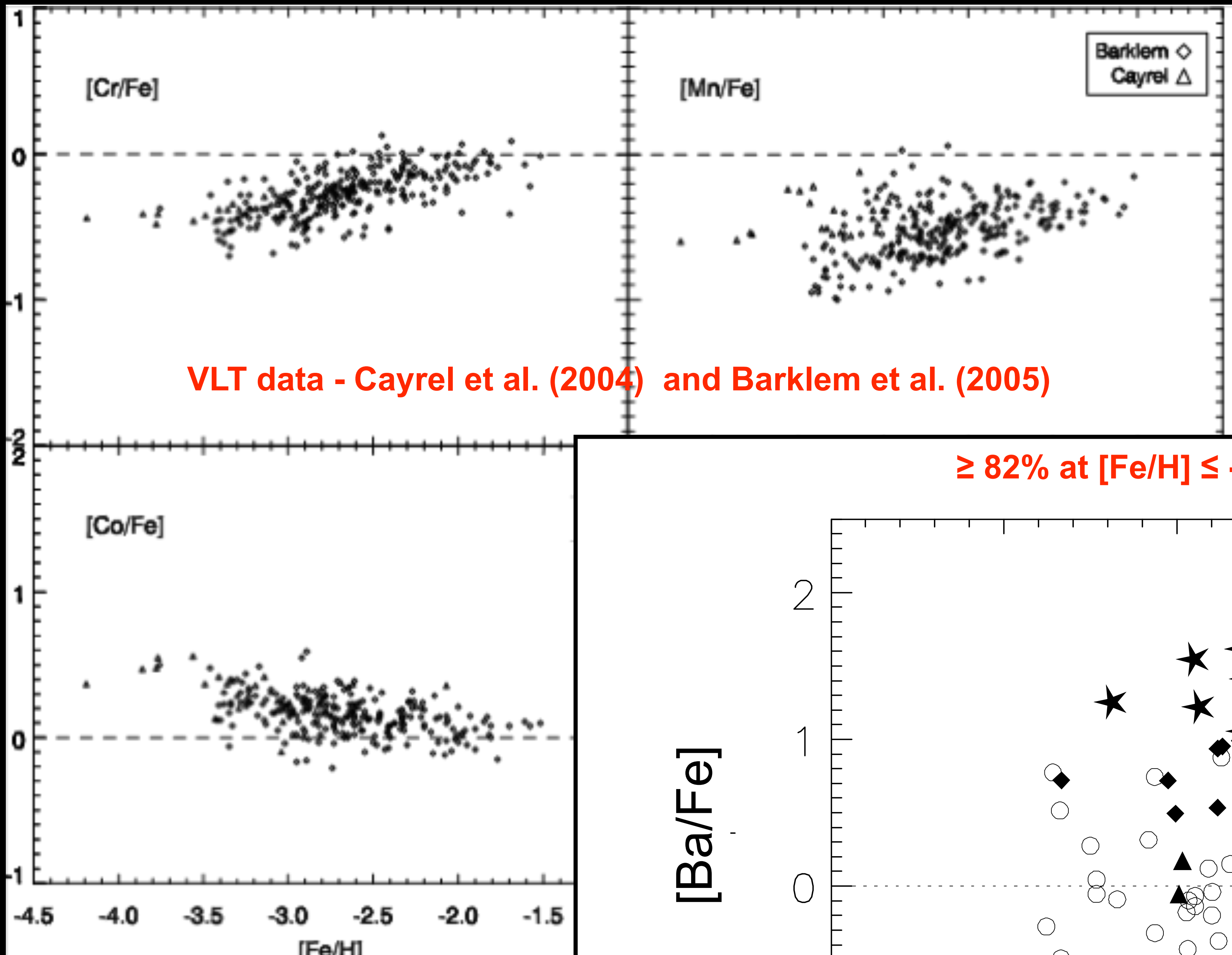
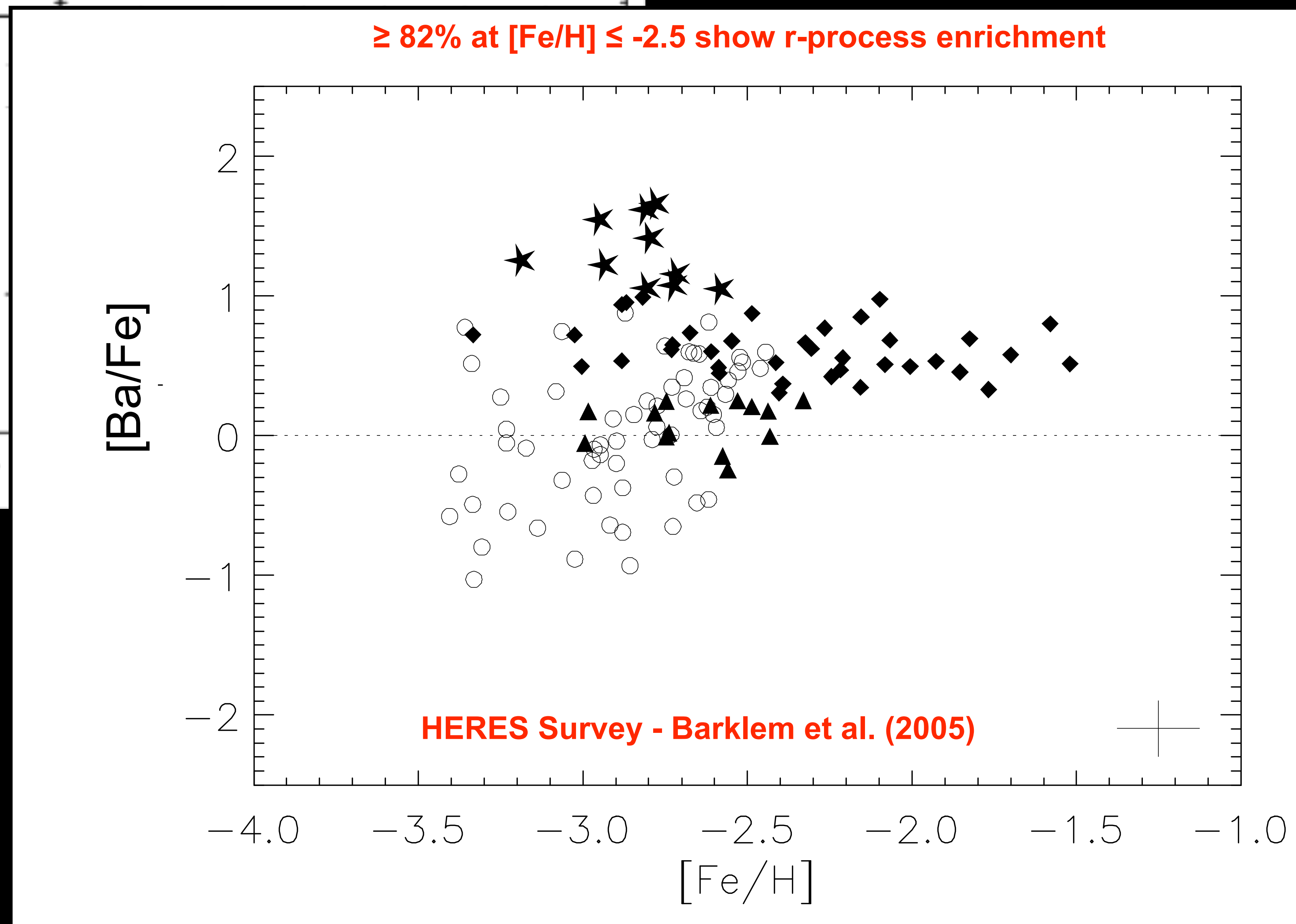
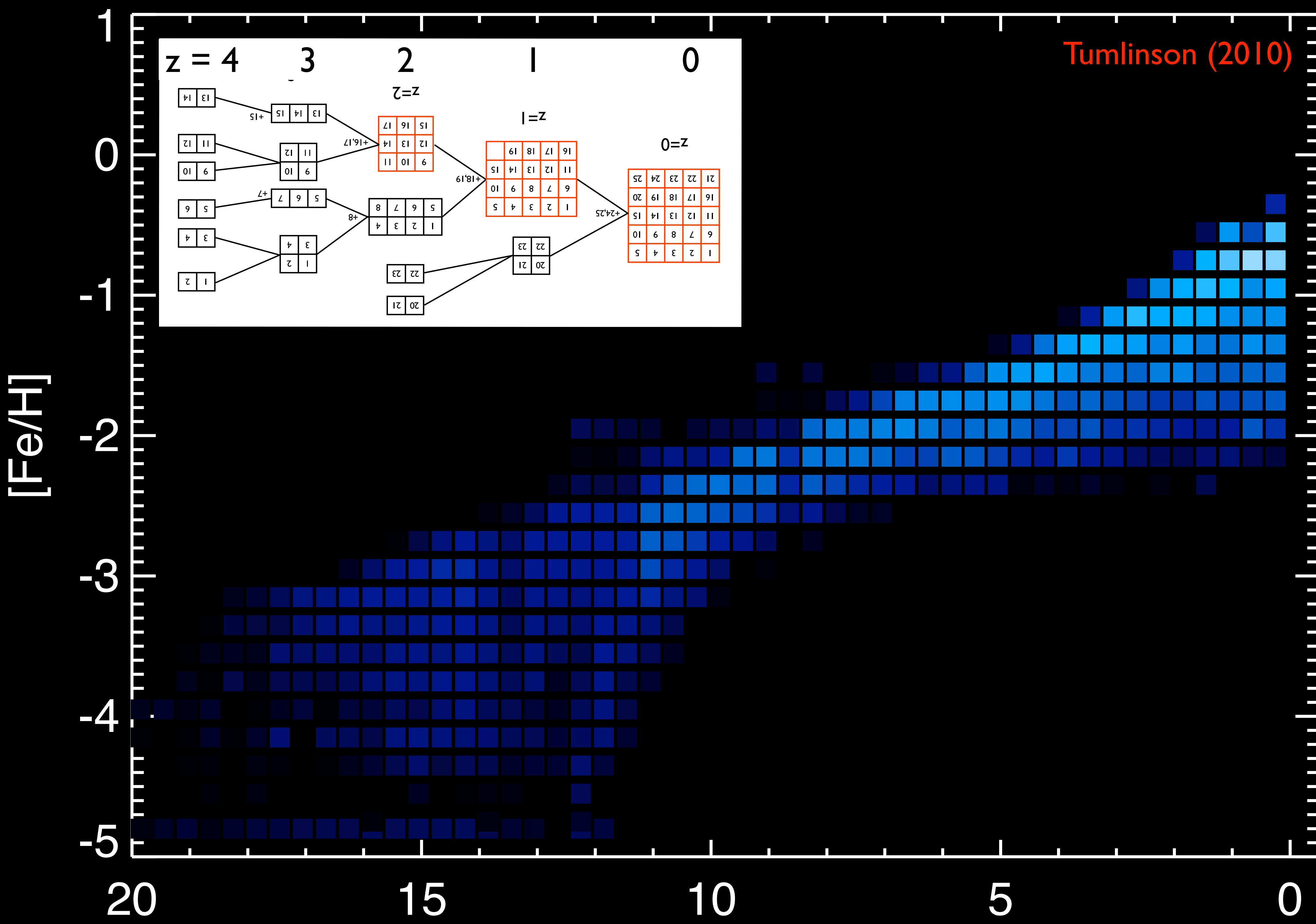
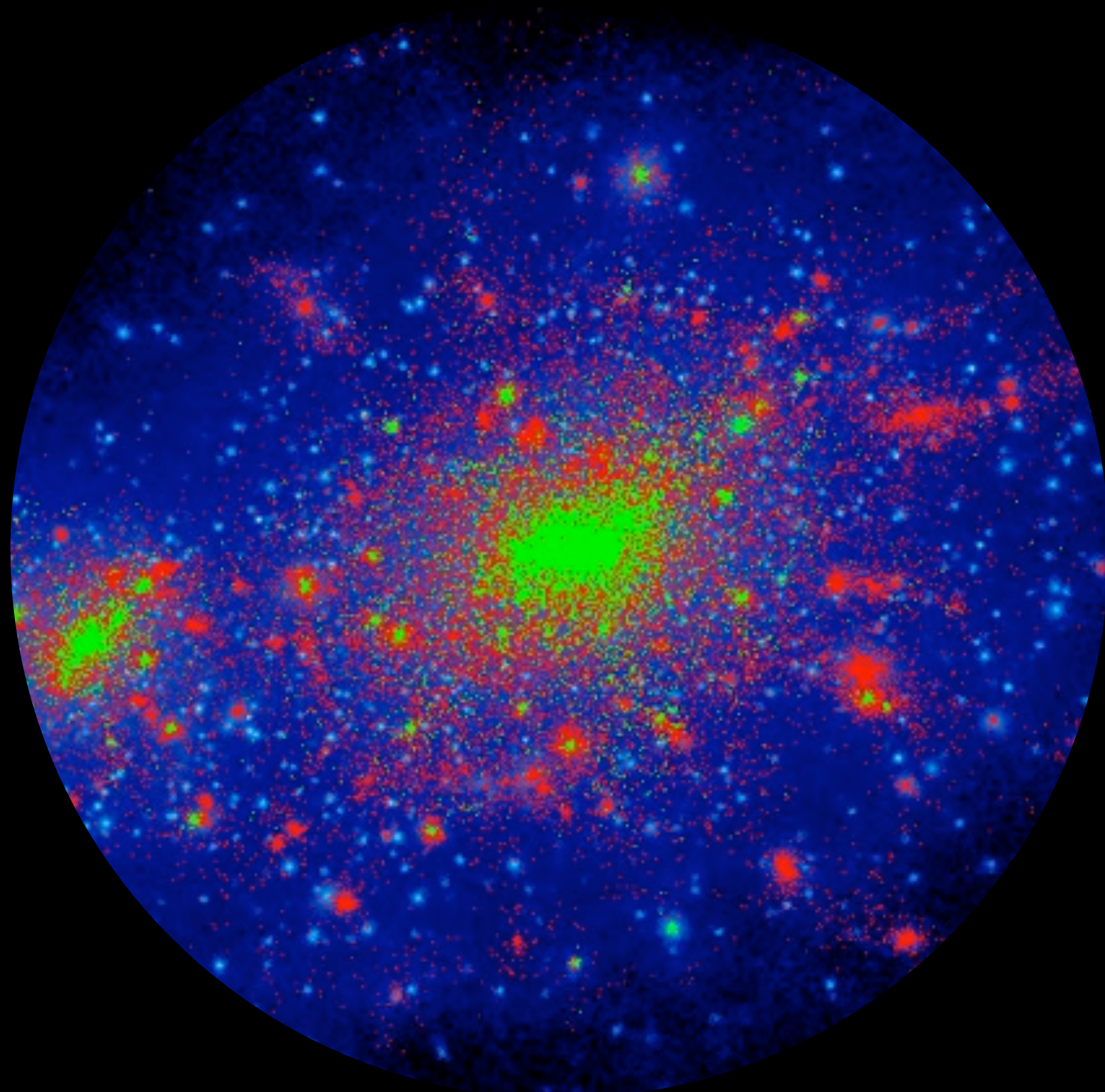




Hierarchical, Stochastic Models and the MW

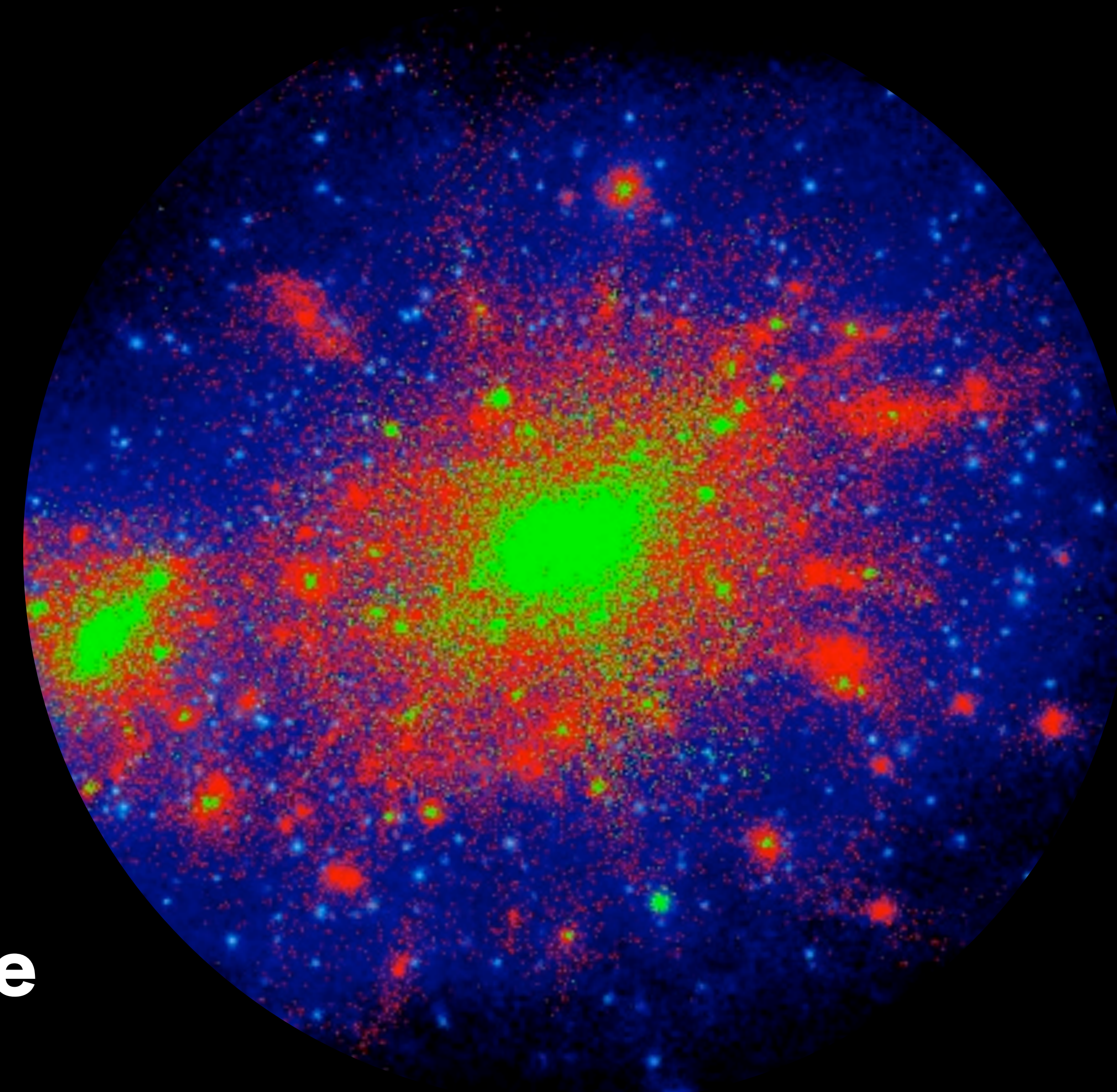


stars formed z > 10
stars formed at all z



[Fe/H] < -3.5

[Fe/H] < -2.0



Chronologically older stars are more centrally concentrated.

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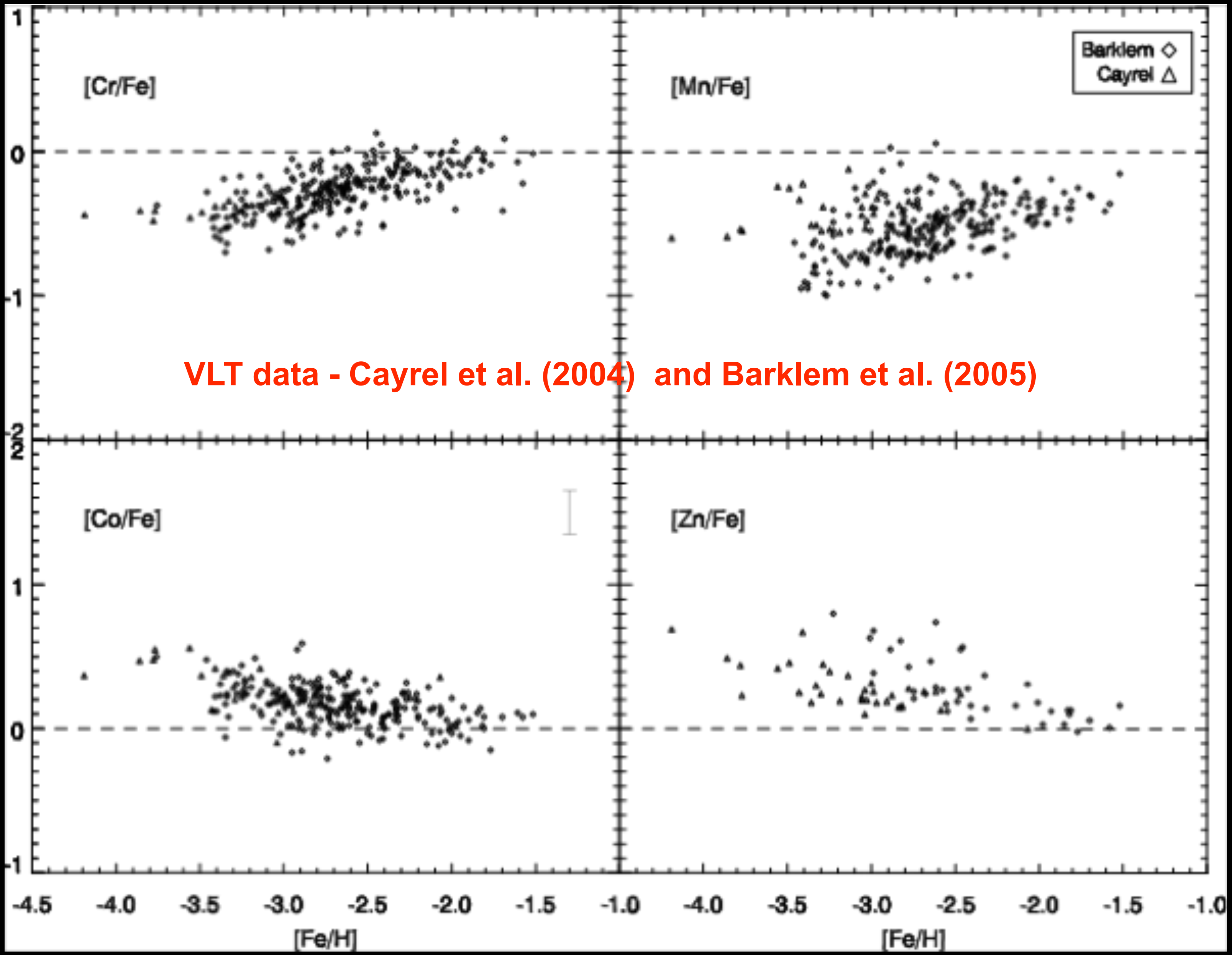
Case Study 1: r-process, iron peak and the first stars



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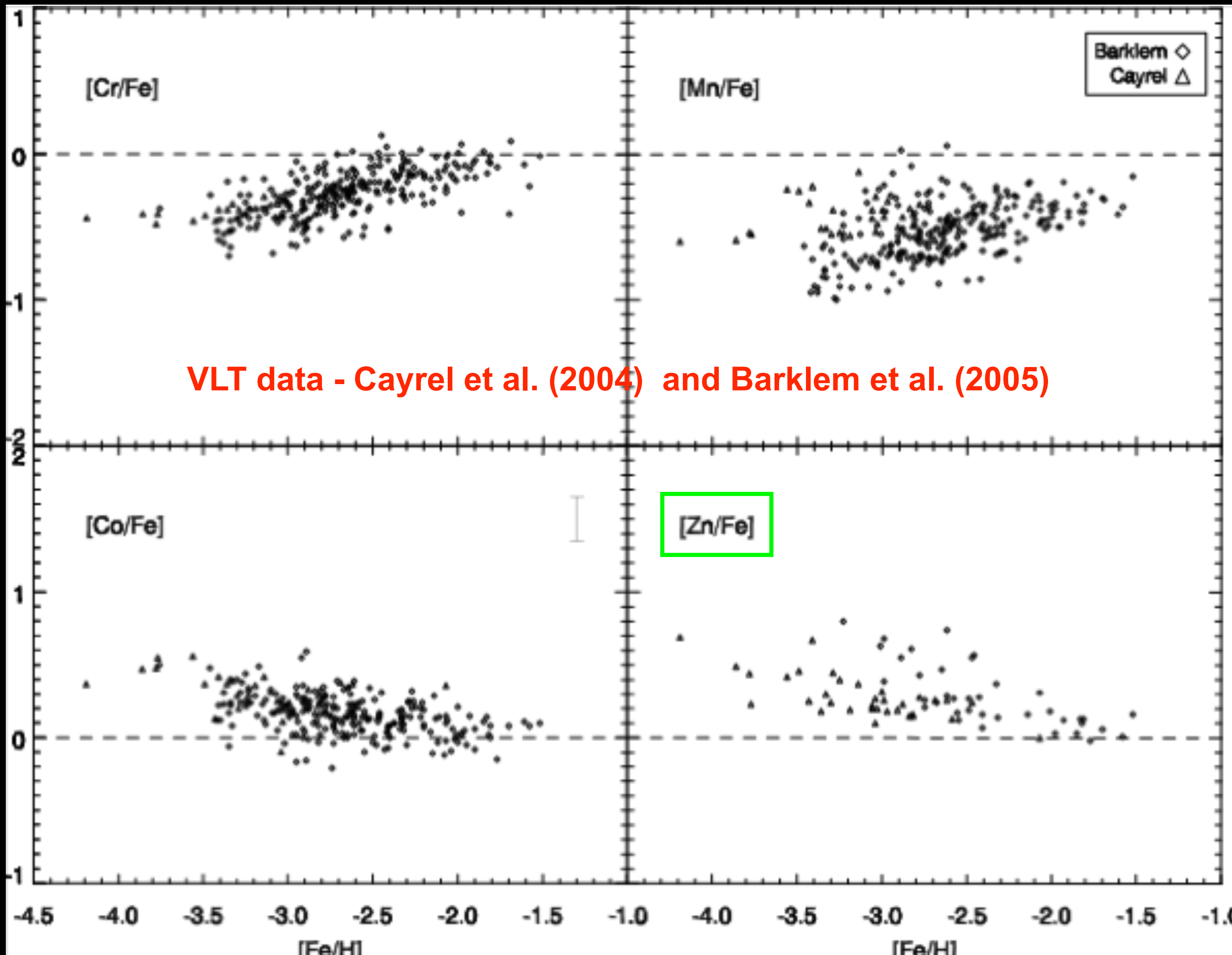

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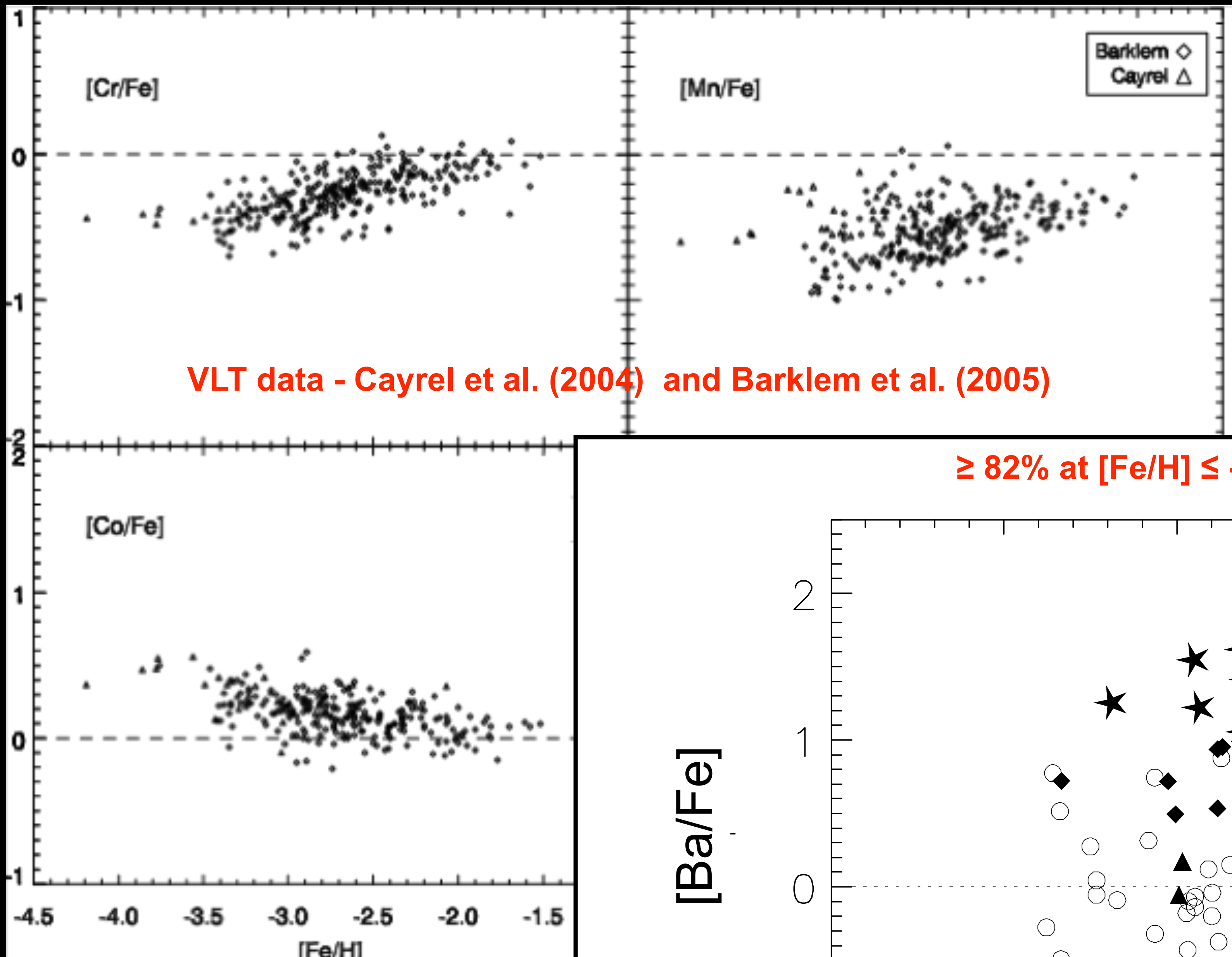
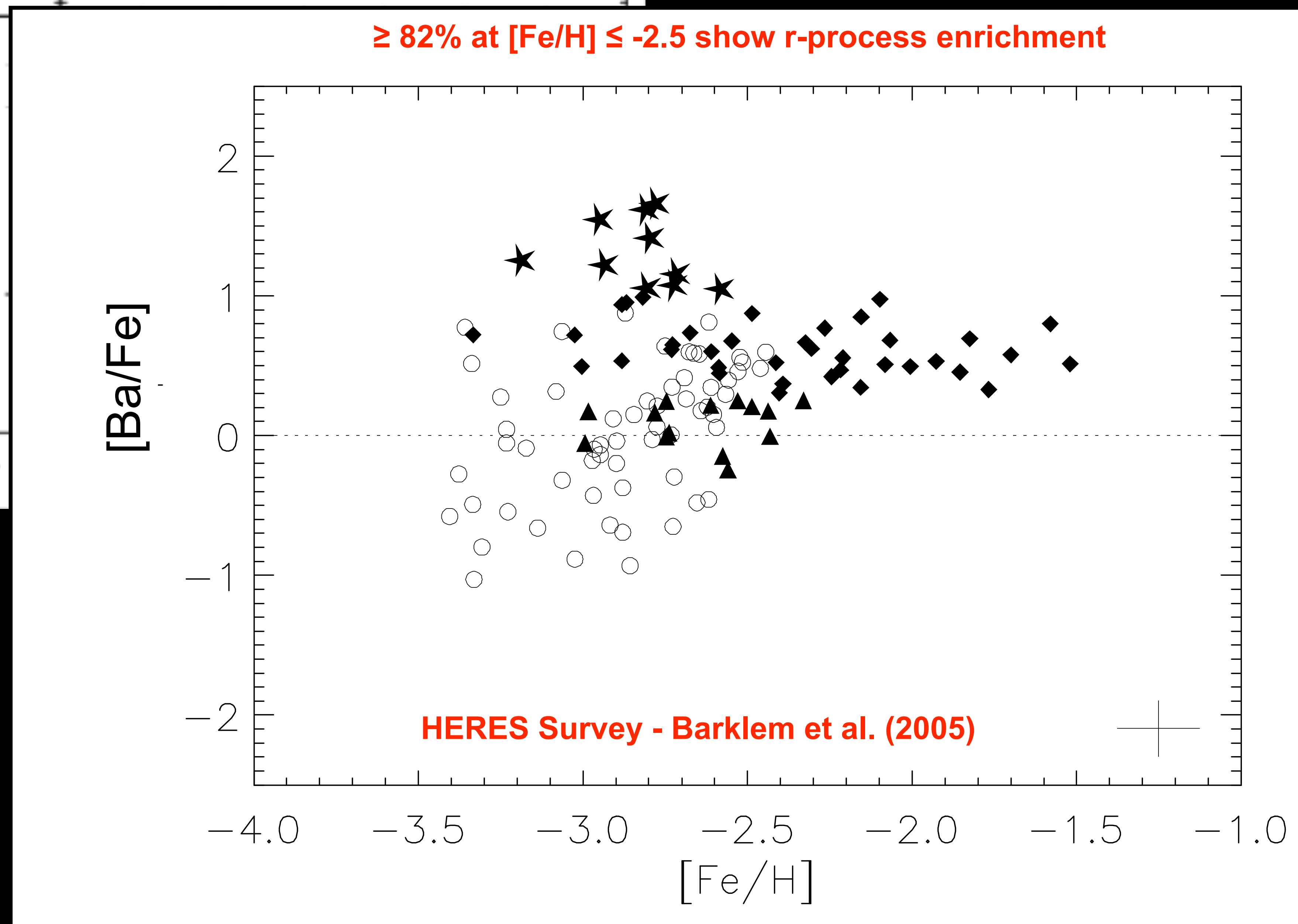
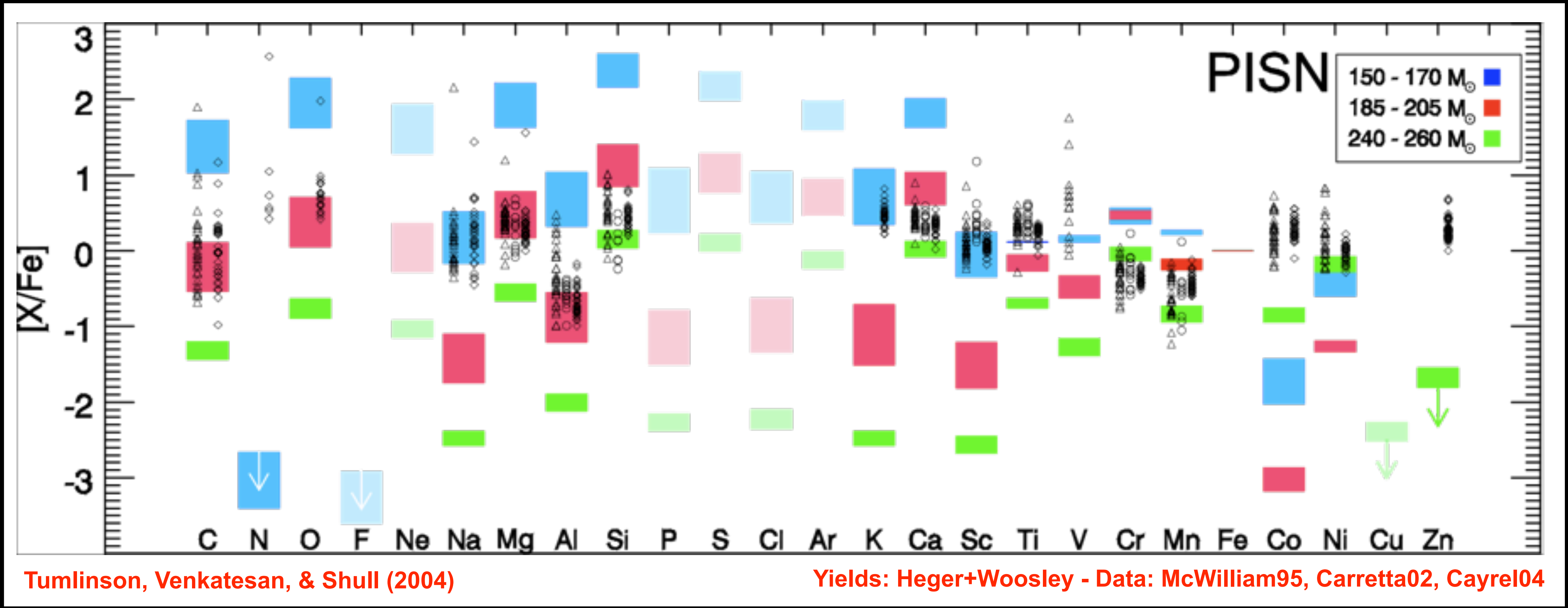




PISNe in Low-Metallicity Stars?

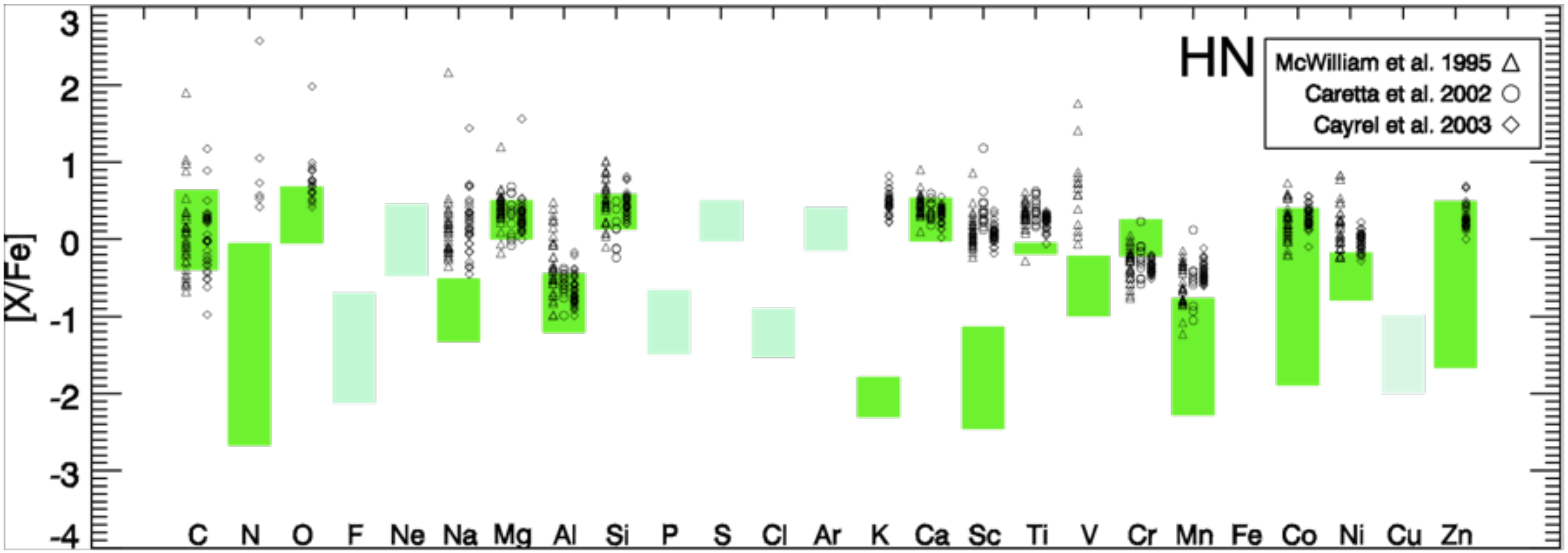


Yields of individual VMS/PISN compared to Galactic Pop II stars:

Widespread r elements rule out IMF of pure VMS (but. . .)

To match observed Fe-peak ratios and odd-even effect, VMS cannot contribute more than ~½ of Fe to early chemical evolution.

Hypernovae in Low-Metallicity Stars?



Tumlinson, Venkatesan, & Shull (2004)

Yields: Umeda+Nomoto04 - Data from McWilliam95, Carretta02, Cayrel04

A Possible Solution: Energetic "Hypernovae" in the First Generation:

- Larger zones of complete Si burning enhance Co, Zn and reduce Cr, Mn, matching observed trends. (Umeda+Nomoto2005).

- For calculated yields, hypernova fraction in first generation approaches $f_{HN} = 1$ to match data on Co, Mn, Cr, Zn, and $f_{HN} > 0.5$ at 90%+ confidence from discrete histories.

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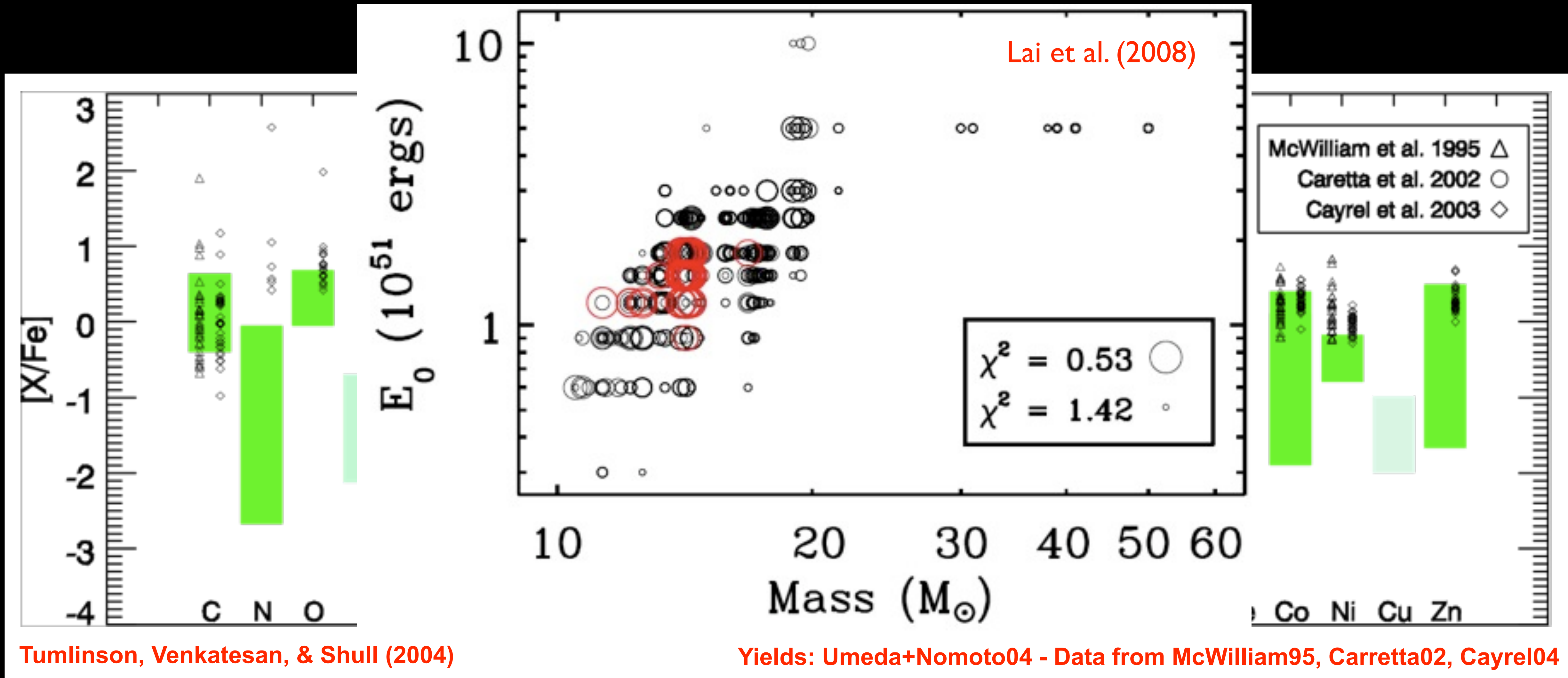

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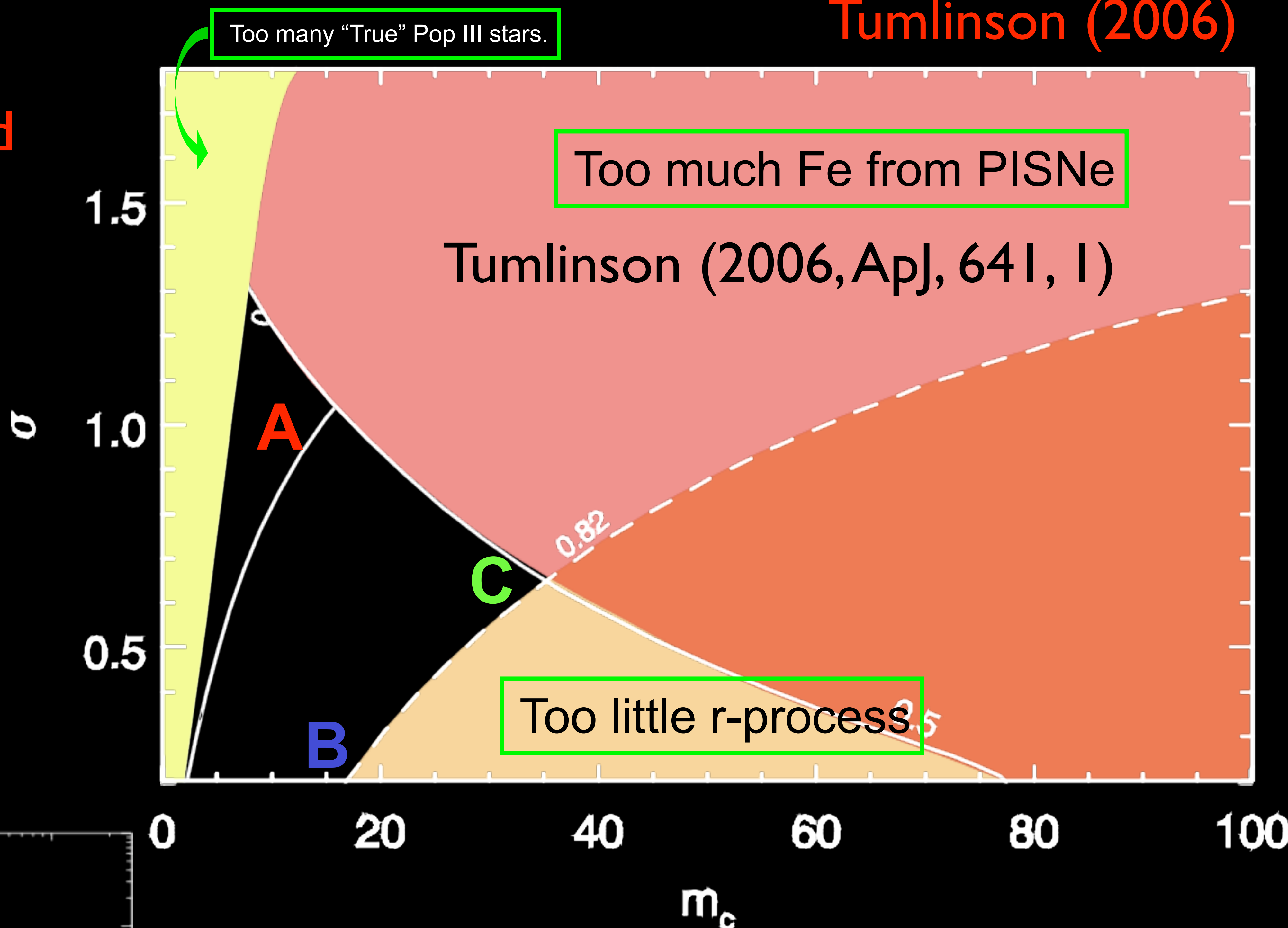
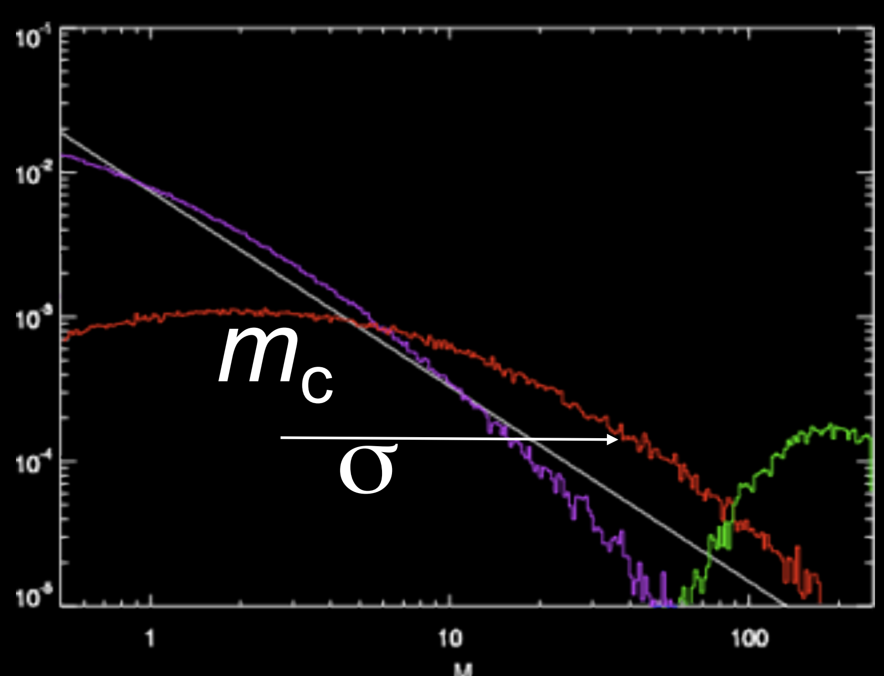
The Fossil Record of the Pop III IMF (so far)

Tumlinson (2006)

PISNe are not needed to explain the observed chemical abundance of Milky Way halo stars.





Observed halo abundances fit in well with the emerging picture of "Pop III.2"; lower mass primordial stars, 10 - 100 M☉, formed in larger HD-cooled halos.

Lai et al.(2008) find ~ 10-20 M☉ is favored mass scale.

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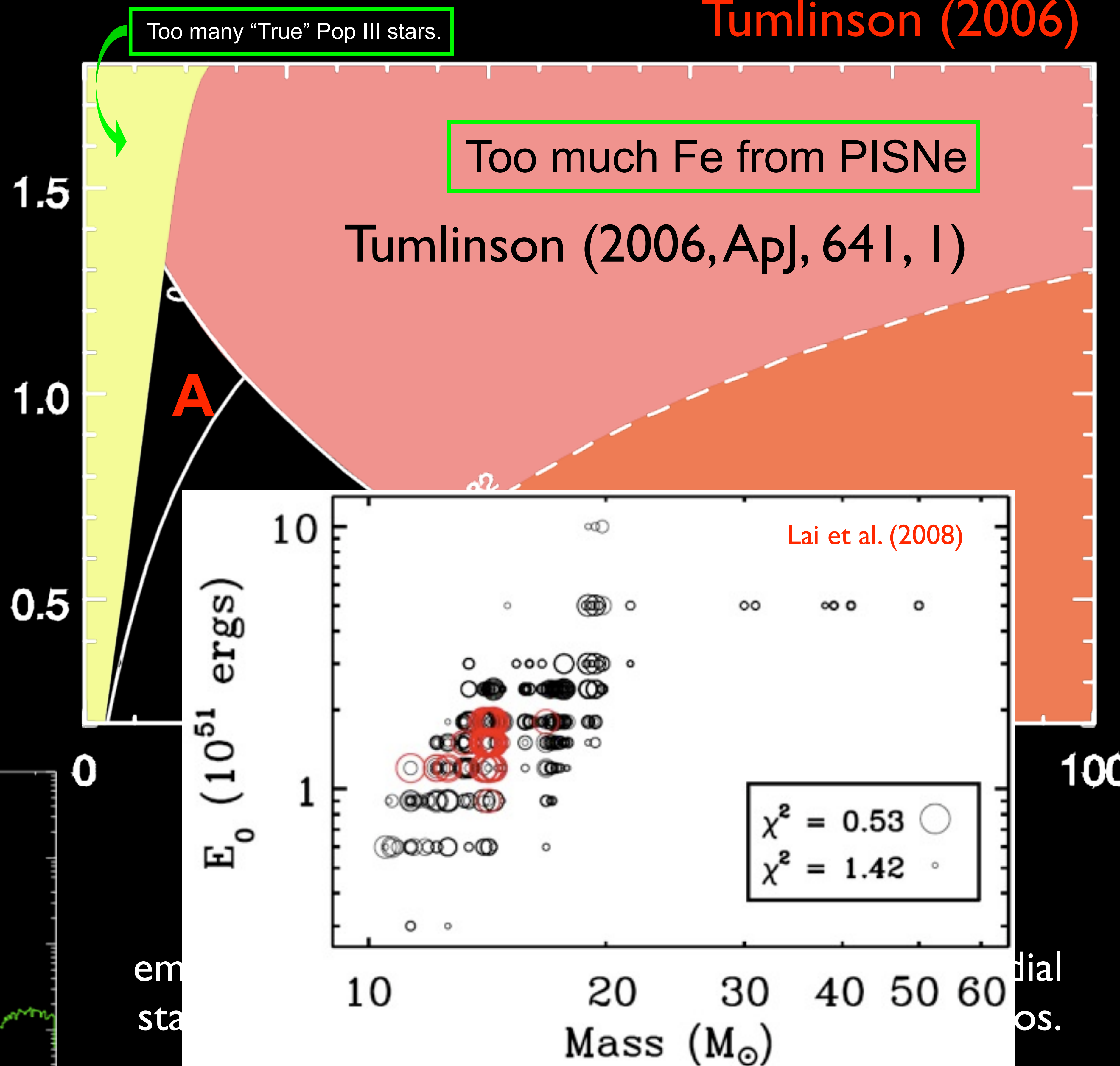

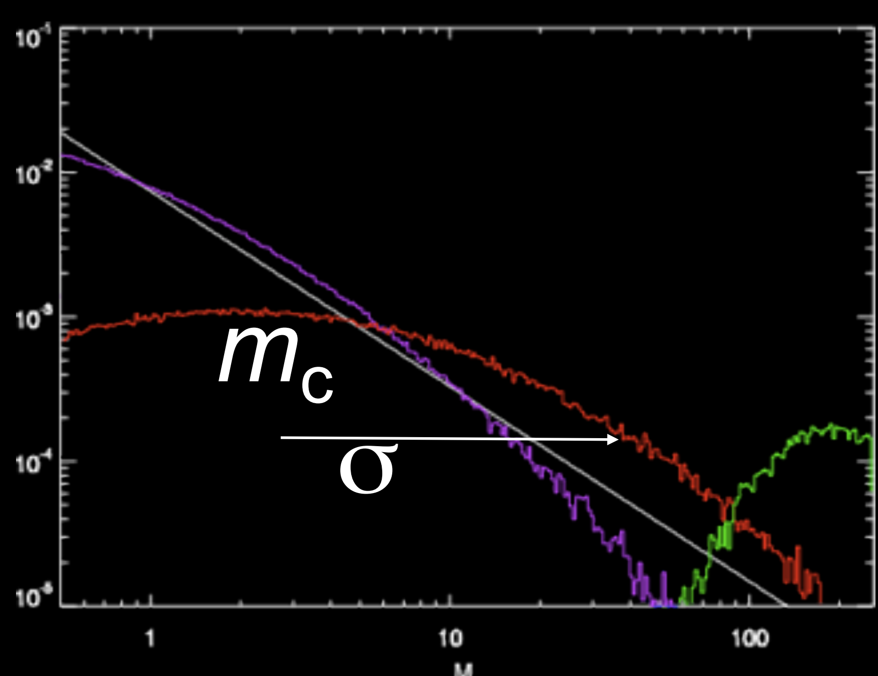

em… dial

sta… os.

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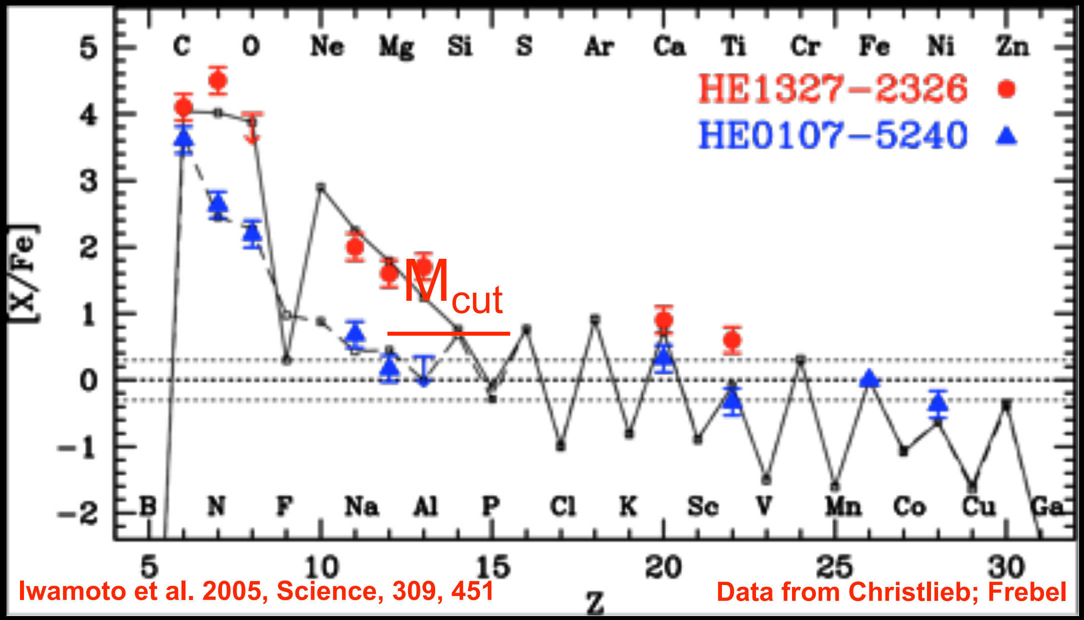
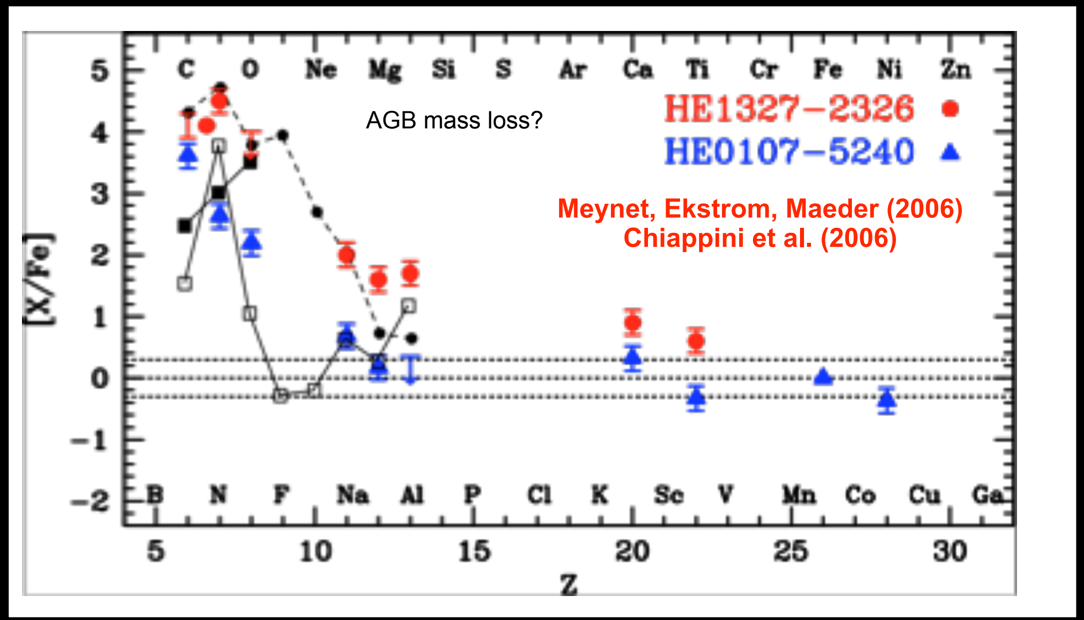
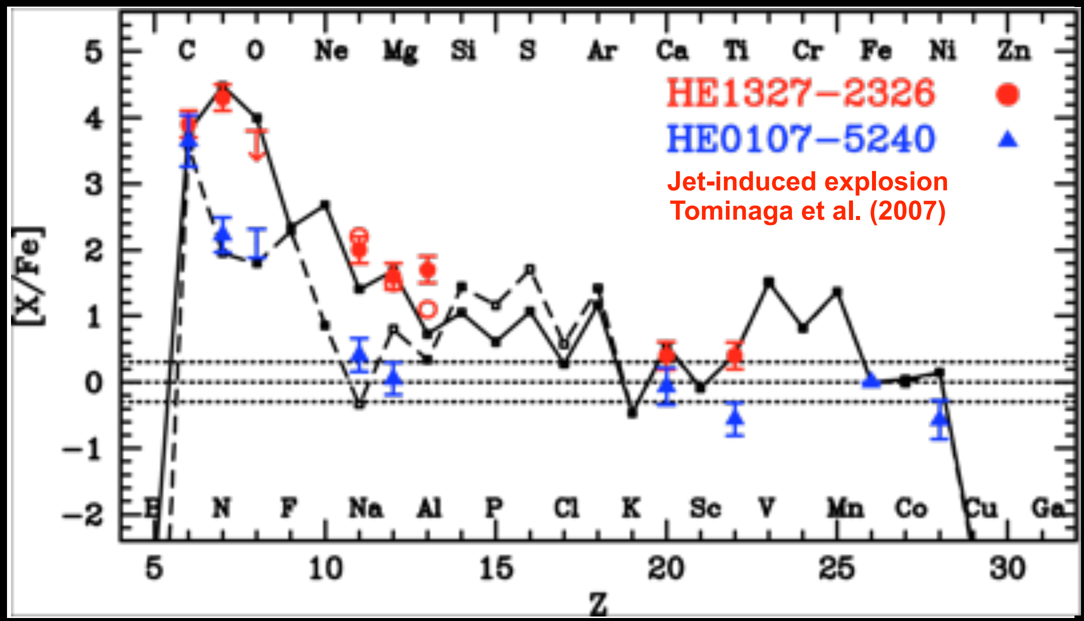


Faint SNe in which light elements escape but heavy elements fall into the black hole? (Iwamoto et al. 2005)

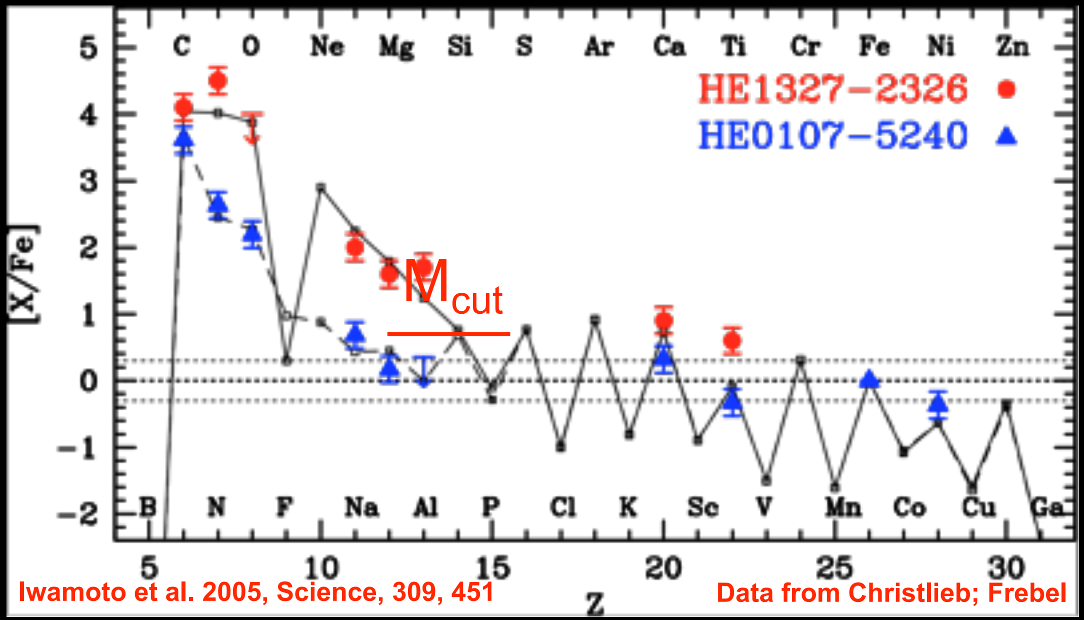


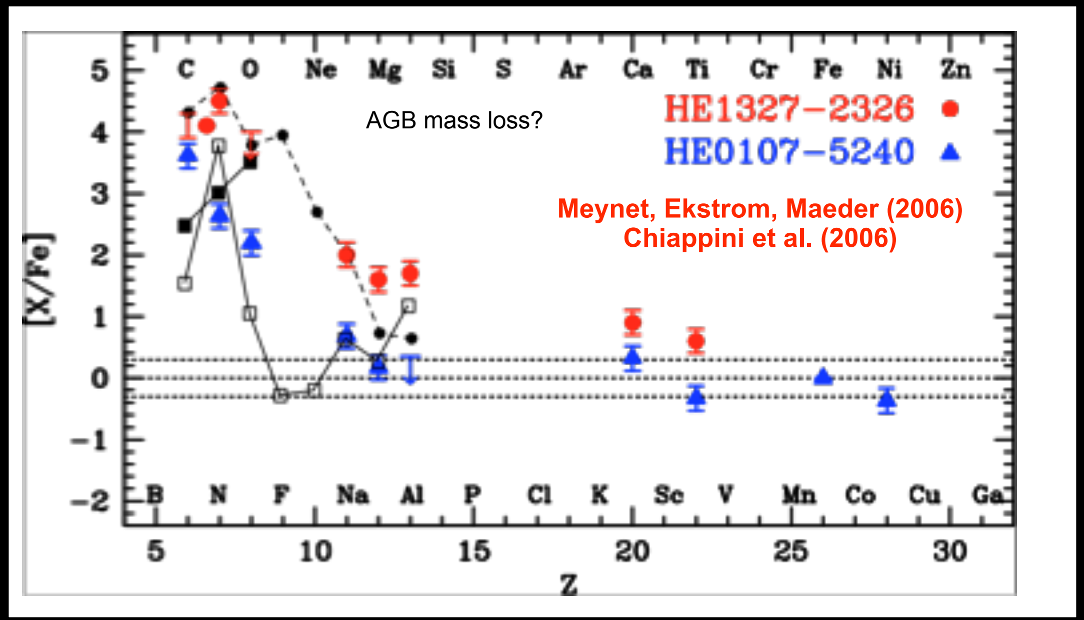
Stellar winds from rapidly rotating Z = 0 stars, or AGB mass loss?

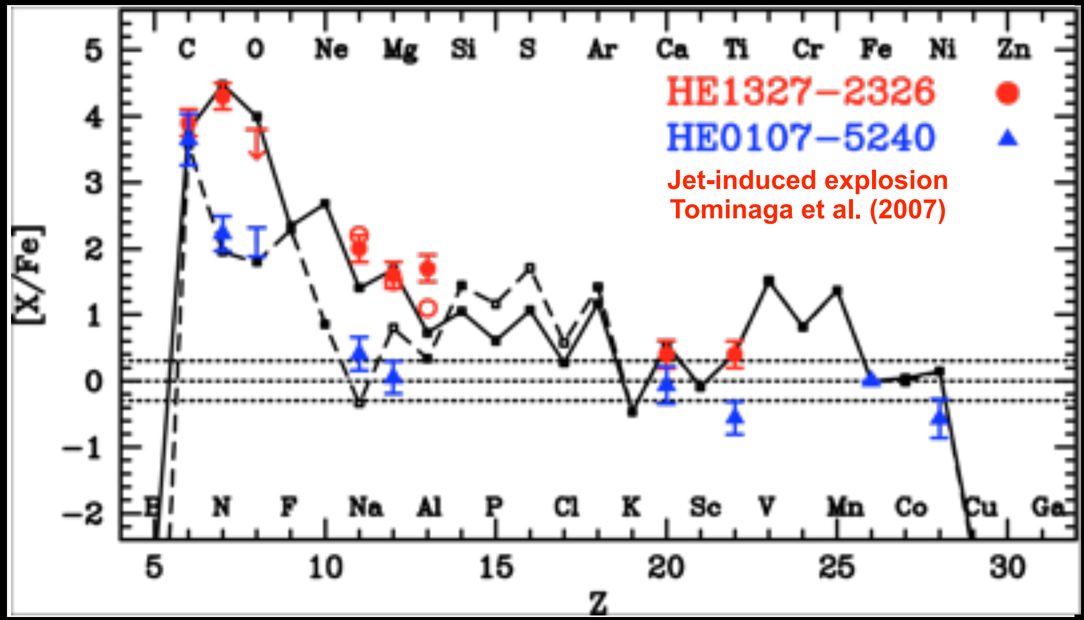


A jet-induced (GRB-like) explosion with mixing and fallback?

Case Study 2: The origins of the HMP stars







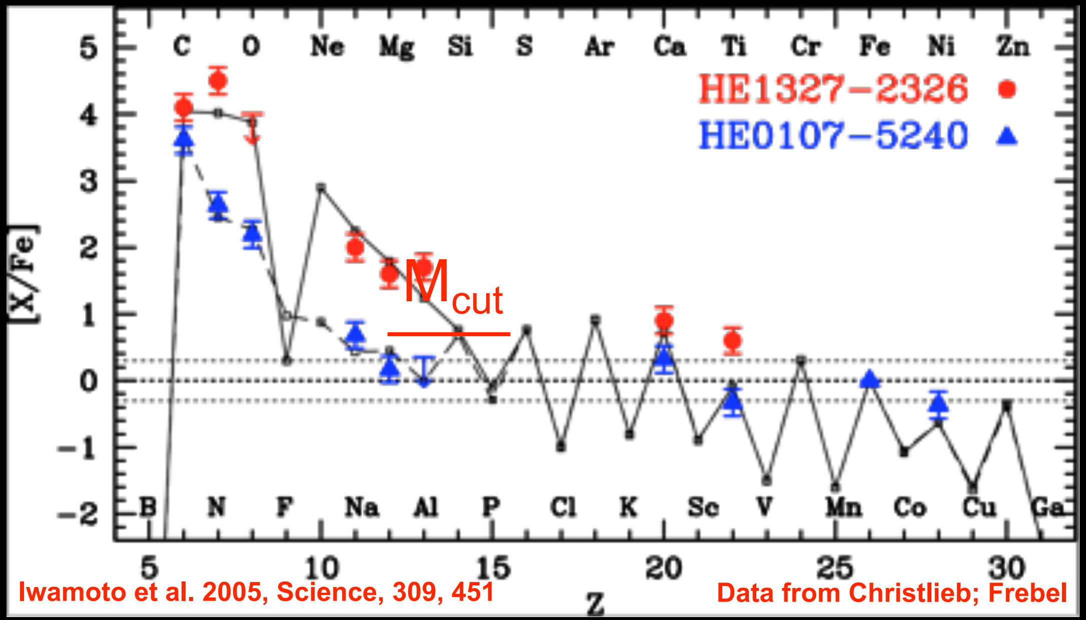
Faint SNe in which light elements escape but heavy elements fall into the black hole? (Iwamoto et al. 2005)

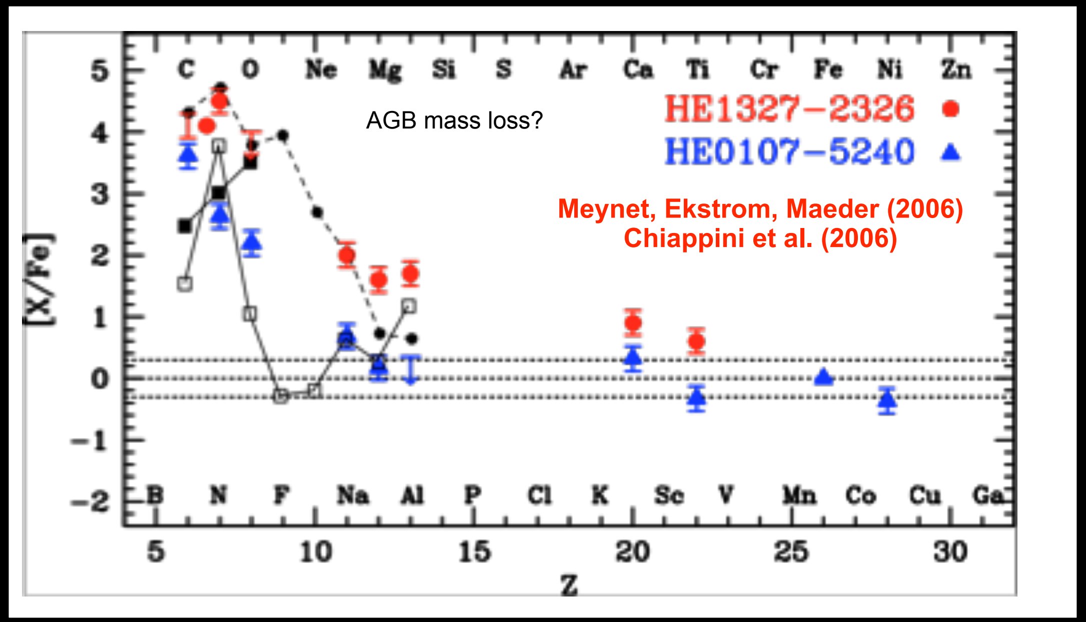
We have "existence proofs" for various unusual abundance patterns.

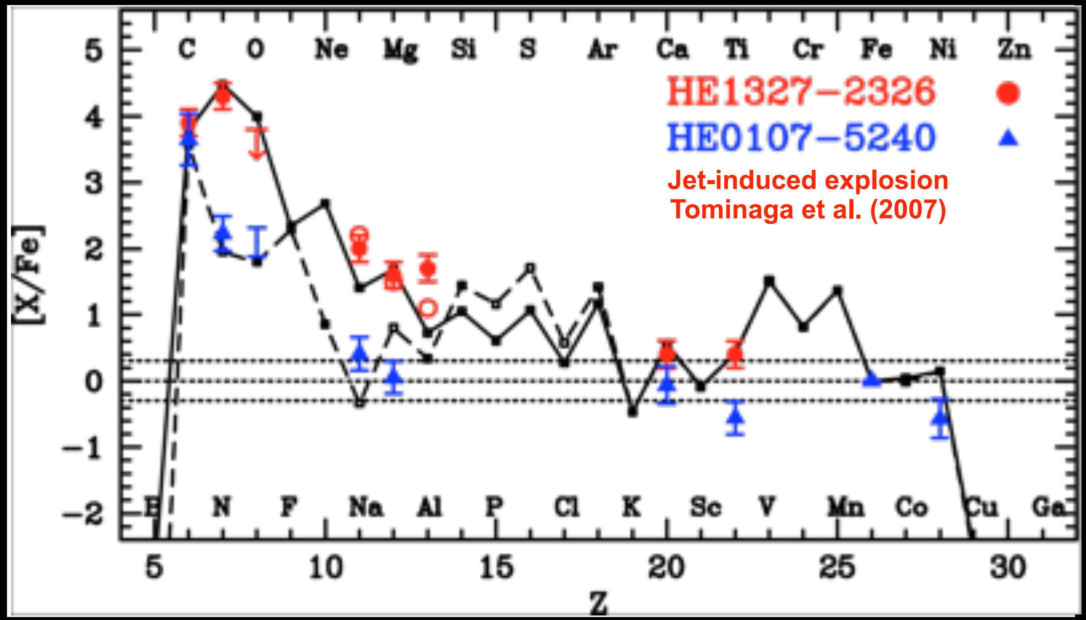
Stellar winds from rapidly rotating Z = 0 stars, or AGB mass loss?

A jet-induced (GRB-like) explosion with mixing and fallback?

Case Study 2:
The origins of the HMP stars







Faint SNe in which light elements escape but heavy elements fall into the black hole? (Iwamoto et al. 2005)

We have "existence proofs" for various unusual abundance patterns.

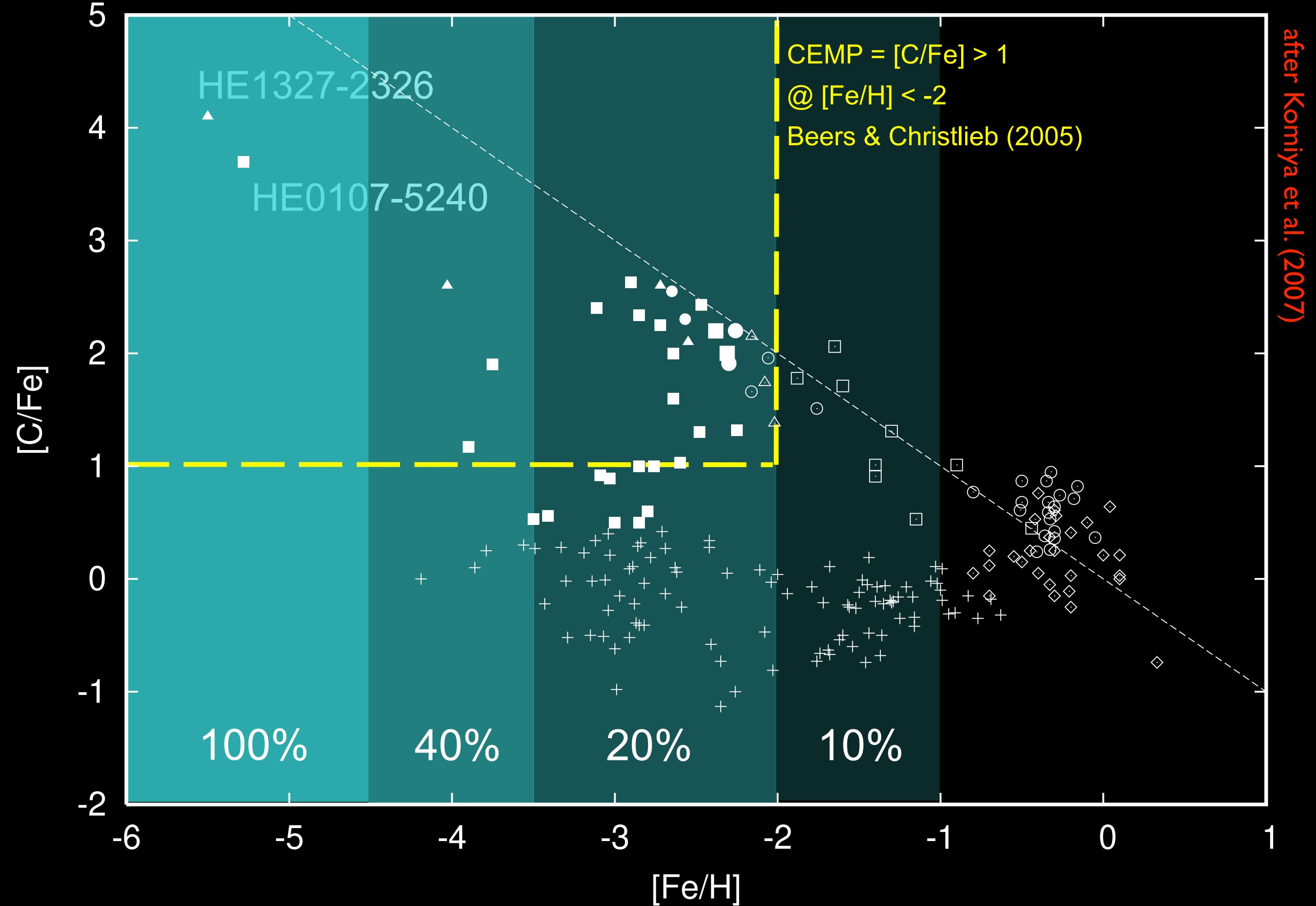
Stellar winds from rapidly rotating Z = 0 stars, or AGB mass loss?

But there are still too many basic mechanisms that can be responsible!

A jet-induced (GRB-like) explosion with mixing and fallback?

Case Study 2: The origins of the HMP stars

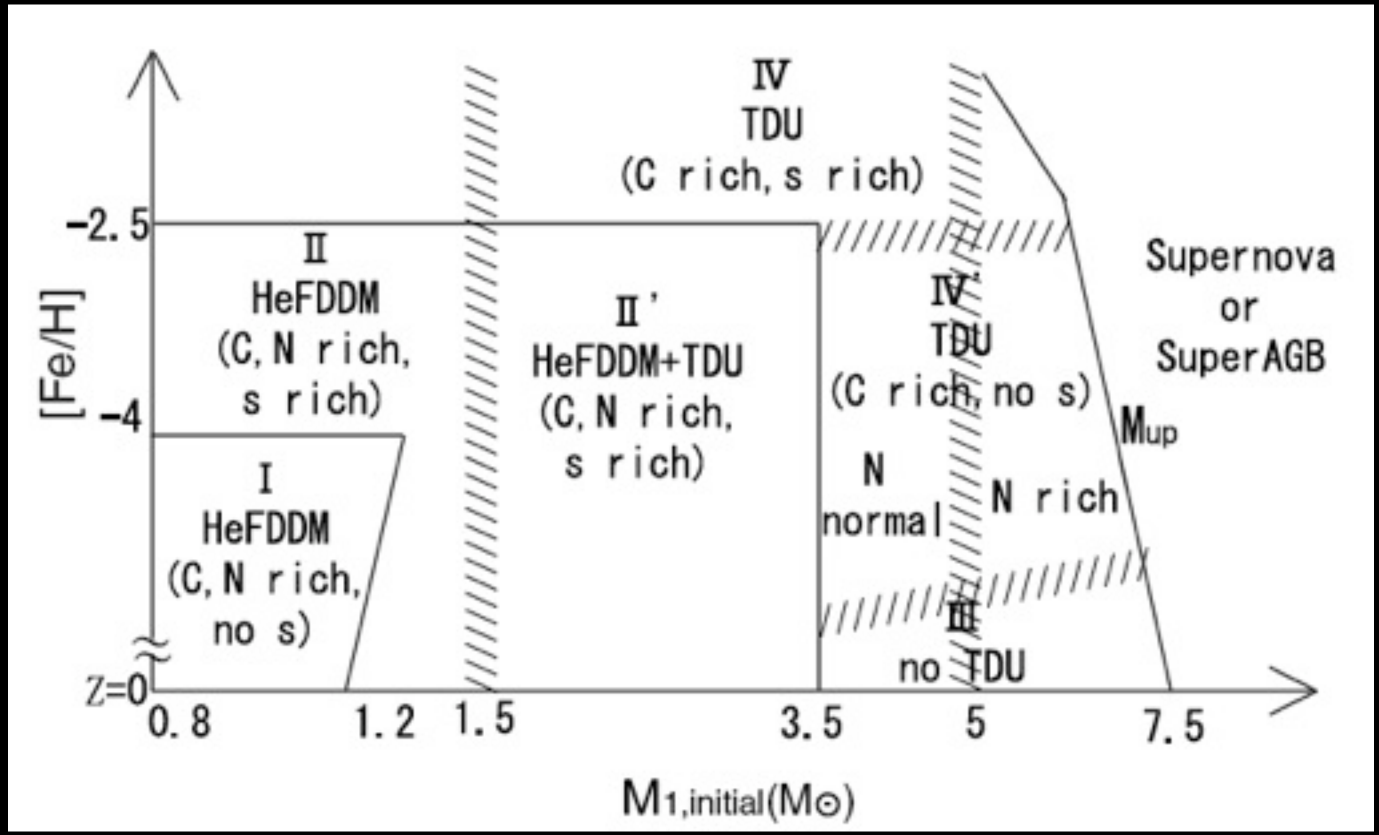
Case Study 3: CEMP Zoo and AGB Nucleosynthesis



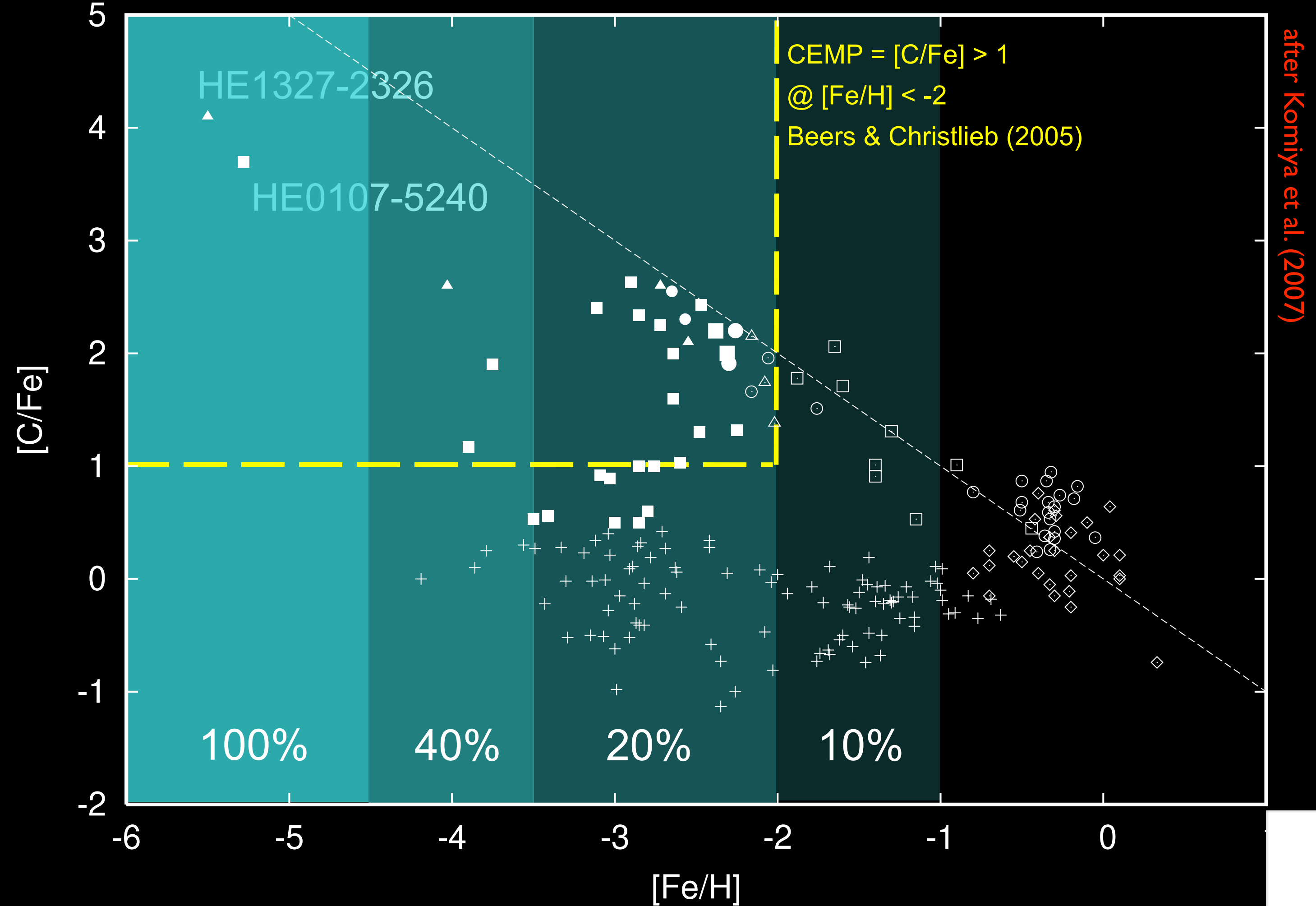
The Carbon-Enhanced Metal-Poor Star Zoo

CEMP
CEMP-no
CEMP-r
CEMP-s
CEMP-r/s

all these phenomena may relate to the mass-and-metallicity dependent yields of intermediate mass stars and AGB (Suda et al. 2006, Komiya et al. 2007, Masseron et al. 2009)



Case Study 3: CEMP Zoo and AGB Nucleosynthesis



The Carbon-Enhanced Metal-Poor Star Zoo

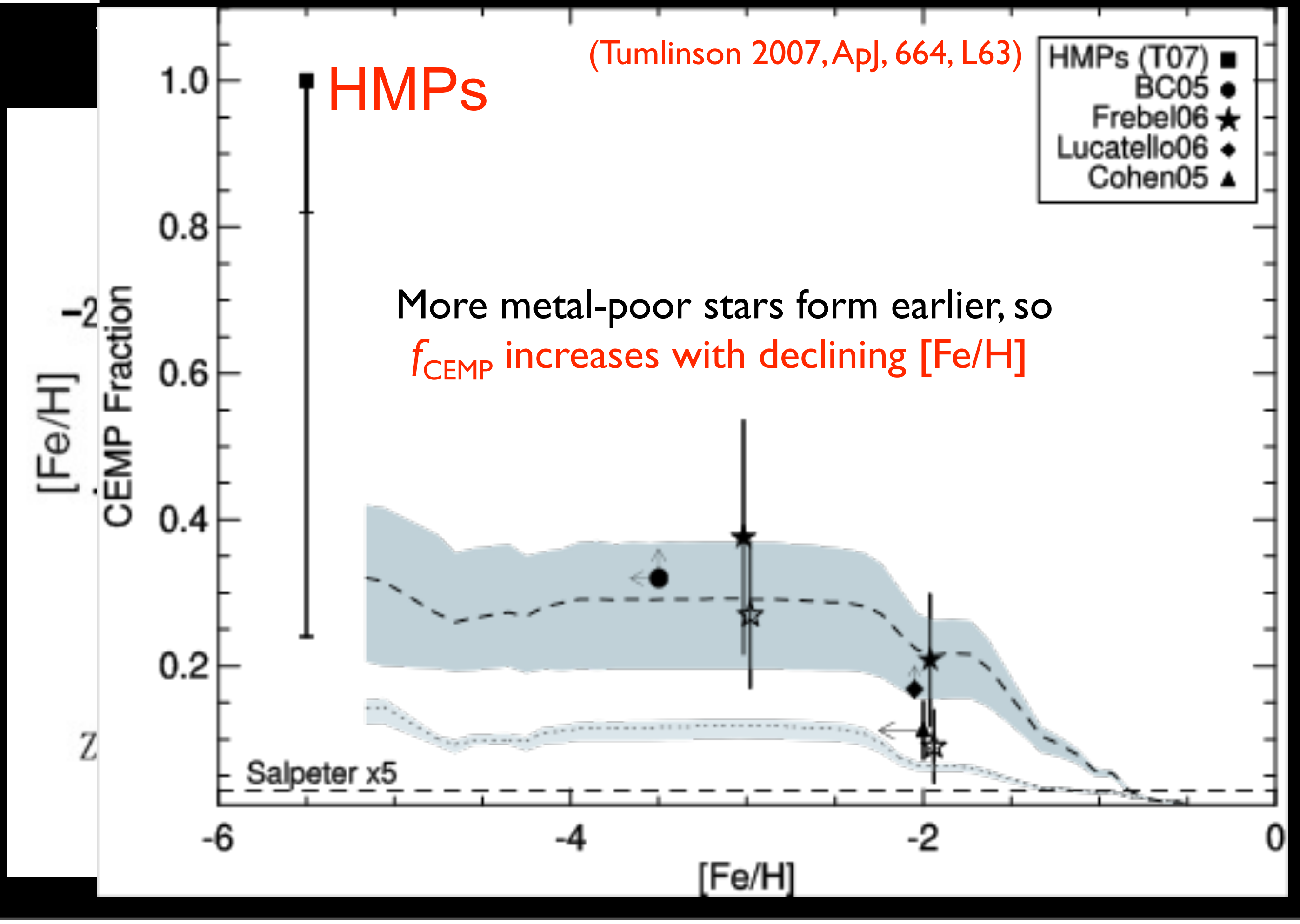
CEMP
CEMP-no
CEMP-r
CEMP-s
CEMP-r/s

all these phenomena may relate to the mass-and-metallicity dependent yields of intermediate mass stars and AGB (Suda et al. 2006, Komiya et al. 2007, Masseron et al. 2009)

A top heavy IMF is indicated (Lucatello et al. 2005; Komiya et al. 2007, Tumlinson 2007a,b) but depends on yields. How can these be independently tested?

$M_J \approx 0.9\ M_\odot\ [T_{CMB}/10K]^{1.70-3.35}$

z = 5, 10, 20 T_{CMB} = 16, 30, 57 K M_C = 2, 6, 17 $M_\odot$



Early CE was Weird

Case Study 1:

We can constrain the primordial IMF using r-process and iron-peak elements, but we need to know the yields of these elements as a function of mass, etc.

Case Study 2:

We can reproduce the abundance patterns seen in the "HMP Stars", with too many non-unique and poorly understood mechanisms. Was it binary mass transfer or exotic supernovae?

Case Study 3:

We can make CEMP stars with AGB mass transfer, but we can't make every animal in the zoo in the correct proportions. Implications for IMF depend on it.

CCE and the MW in Four Easy Lessons

Lesson 1

The “Fossil Record” can fill a gap in our high-z knowlege.

Lesson 2

Early Chemical Evolution is Hierarchical and Stochastic.

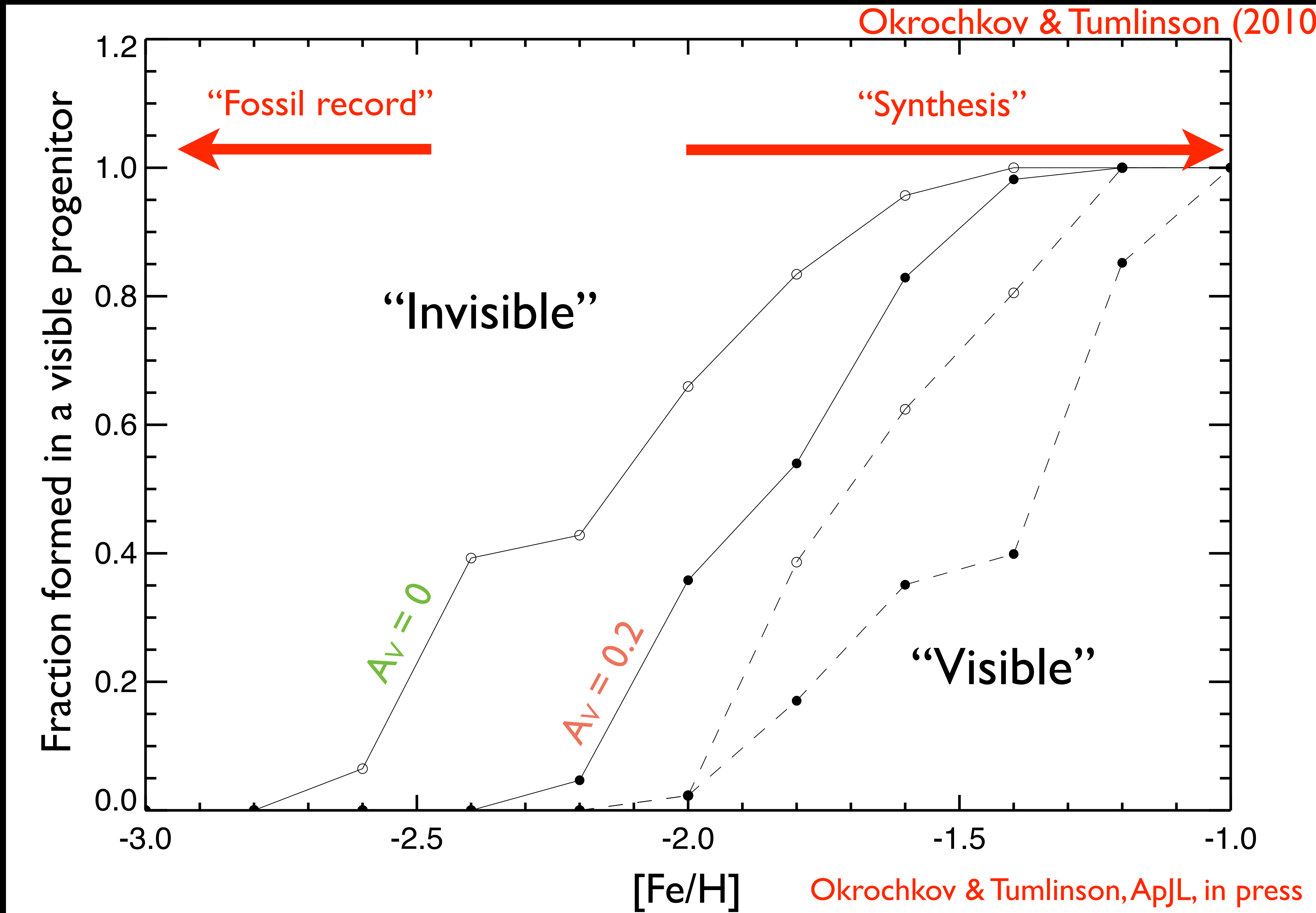
Lesson 3

Early Star Formation and Nucleosynthesis Was “Strange”

Lesson 4

Pursuing High-z / Low-z links is essential.

The High-Redshift Visibility vs. Metallicity



Recall: We have estimated that the majority of MW halo stars with [Fe/H] < -2 formed in galaxies that would be too faint for JWST in the high-z Universe.

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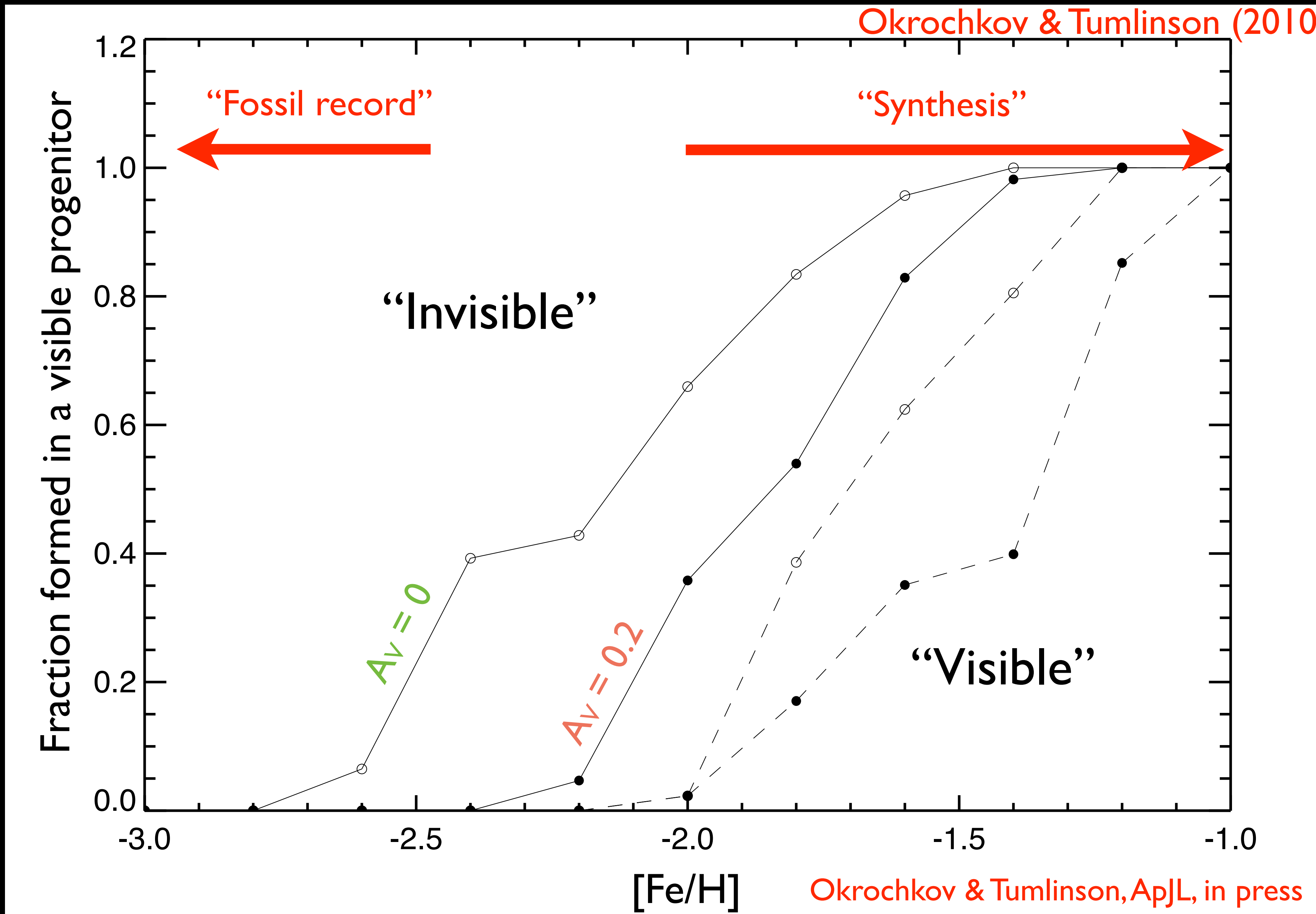
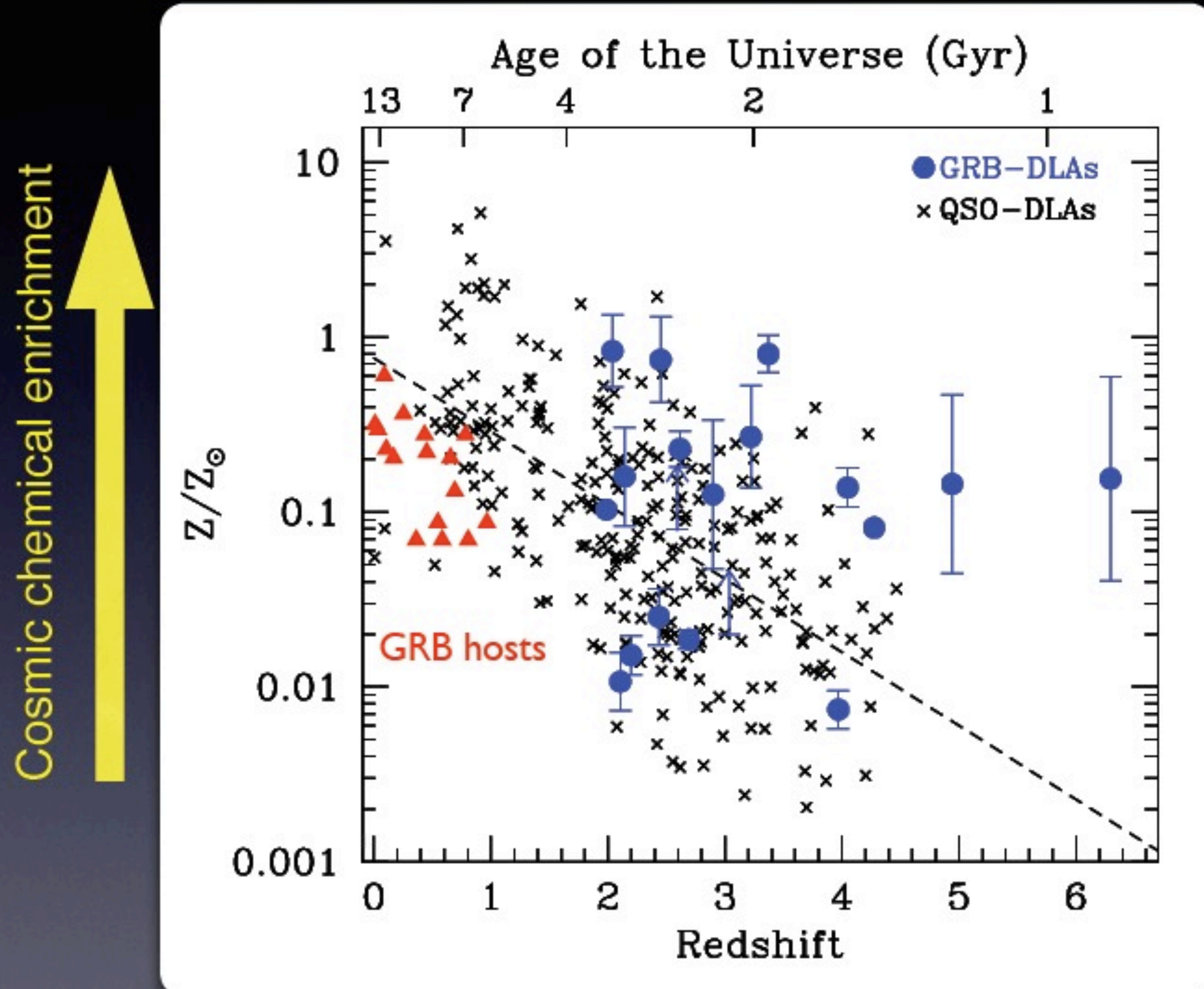


Recall: We have estimated that the majority of MW halo stars with [Fe/H] < -2 formed in galaxies that would be too faint for JWST in the high-z Universe.

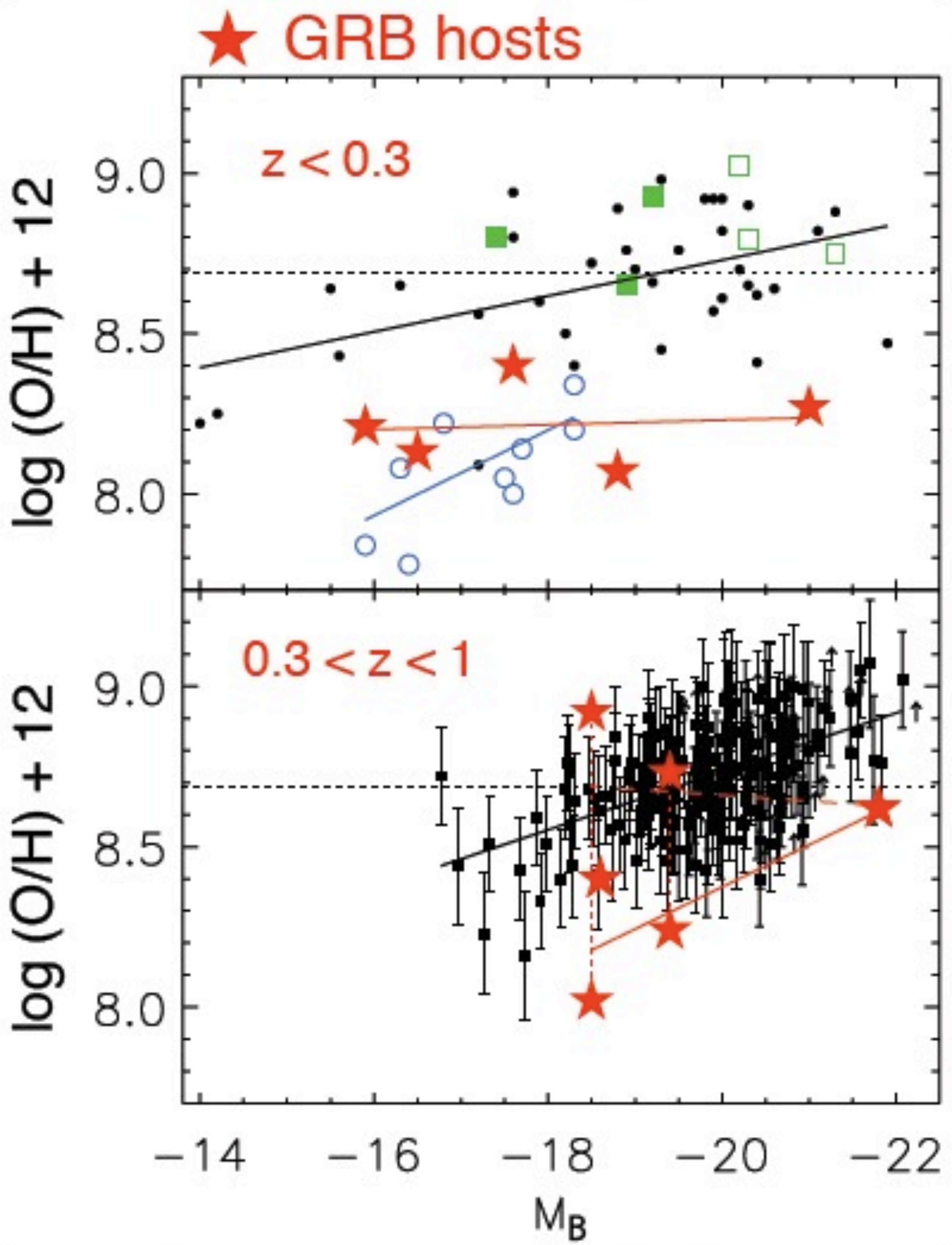
Can we do the same experiment with high-z GRBs?

Cosmic chemical evolution with GRBs

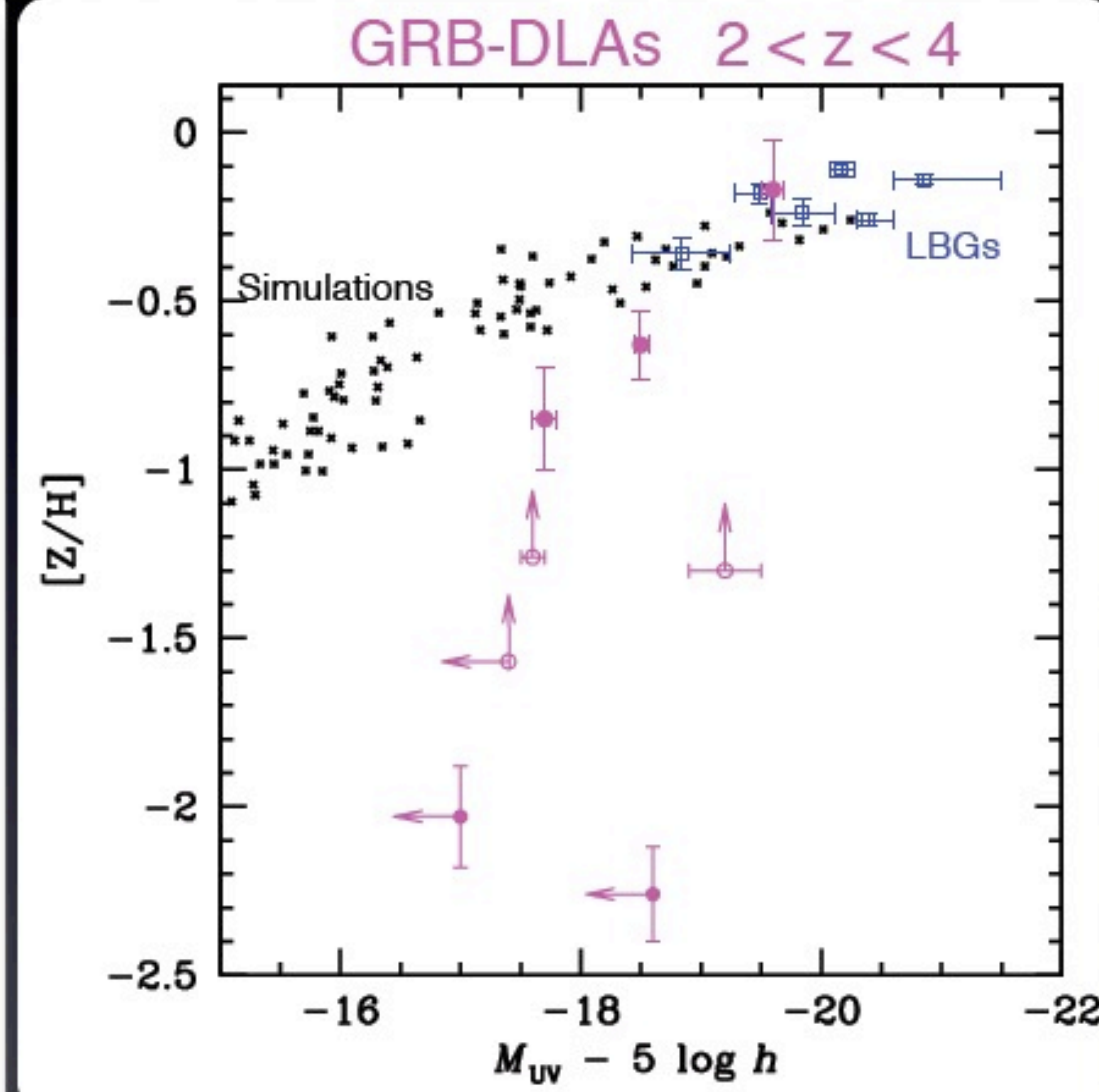


Updated version of
Savaglio, Glazebrook & Le Borgne (2009)

Mass-luminosity relation in GRB hosts



Levesque et al. (2009)



Chen et al. (2009)

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So pursuing GRBs as chemical probes is a great idea!

Questions Posed by the MW's Lessons

- Early chemical enrichment is stochastic, and in galaxy spectra we see population-averaged abundances. Can we measure local, "instantaneous" abundances at high redshift?

- Early chemical abundances in metal-poor halo stars are "weird". If these trends (e.g. CEMPs) are caused by exotic supernovae, can we find at high z the pockets of gas they have produced?

- If we can get GRB probes at $z > 6$, what sensitivity will they have to metallicity (< -2) and to relative abundances?

Questions and Issues for Discussion

- We know that early chemical enrichment ($z > 6$) is stochastic, weird, and related to the IMF, but that it is a crucial window into star formation at $z > 6$.
- Direct observations of starlight for [Fe/H] < -2 MW progenitors are beyond the reach of JWST.
- So what can a GRB-focused mission do to complement this low-redshift “fossil record”?
- Mission “desirements”:

1. Statistical sample of absorption-line probes of galaxies at $z = 6 - 10$.
2. Obtain galaxy mass-metallicity relation at epoch of reionization (Already being done with GRB-DLAs, but how far in z can we go?)
3. Measure relative abundances for C, Fe, etc. Are they “weird”?